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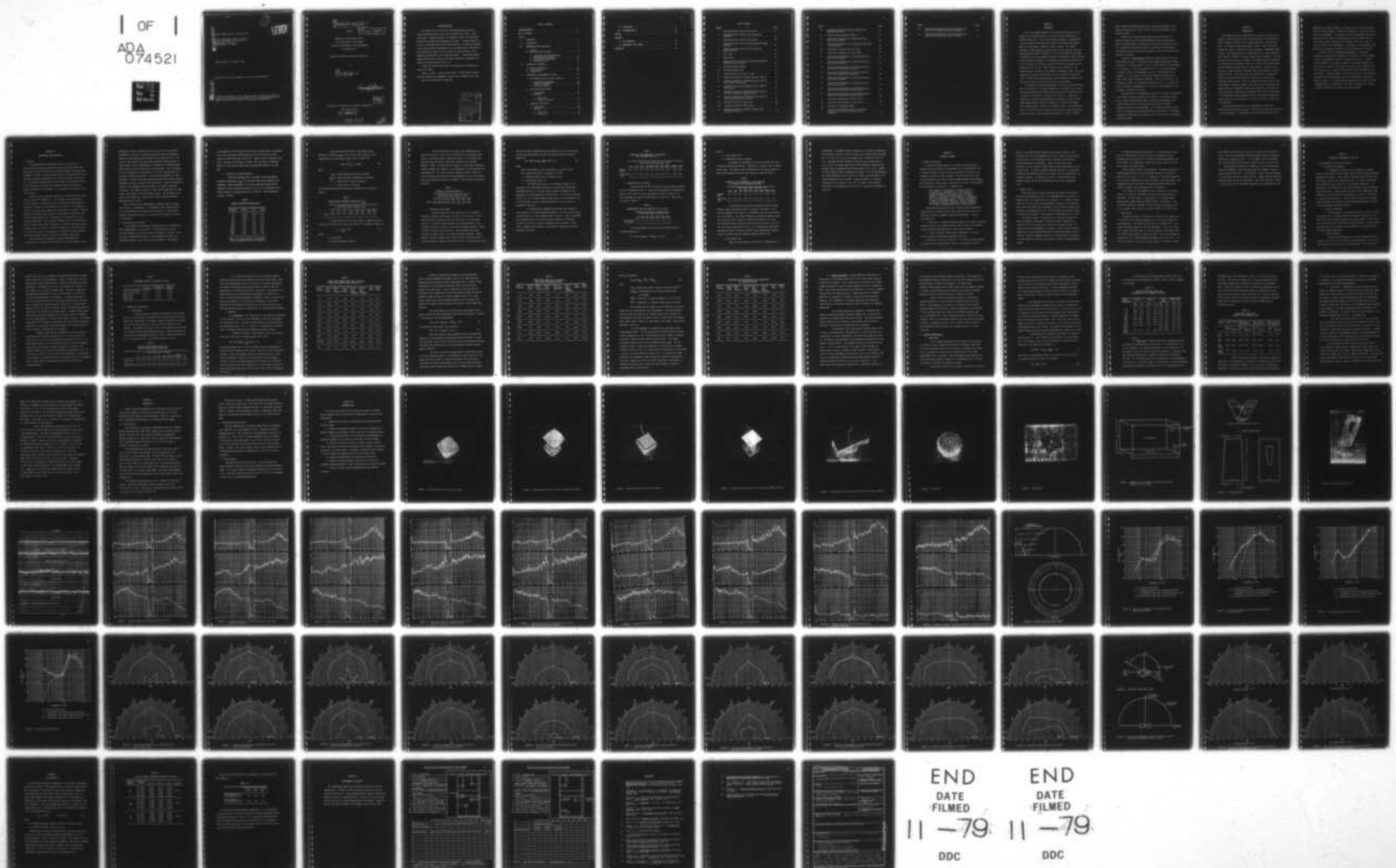

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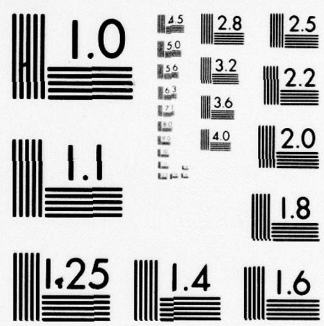

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SOUND POWER LEVEL OF FIRE ALARMS

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Final Report, 27 August 1979

A thesis submitted to the Graduate School of the University of Notre Dame in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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A Thesis

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by

(10)

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CHAPTER I

BACKGROUND

One of the loudest complaints that apartment dwellers voice concerning their living conditions is the lack of sound insulation in apartment structures. As the trend towards apartment and condominium living increases, both builders and buyers are becoming increasingly aware of the acoustical aspects of these buildings. The Federal Government's high emphasis on noise control in the industrial area with the Occupational Safety and Health Act of 1972 has spread to the urban environment as well and heightened everyone's awareness of noise pollution. If this awareness continues, the complaints from apartment dwellers may soon be silenced as buildings become more effectively designed from an acoustical point of view. This, however, poses a conflict to the effectiveness of residential and commercial emergency alarms. The better designed a structure is acoustically, the less effective an alarm becomes. Recently there have been major fires followed by complaints that the alarm could not be heard in all parts of the building.

The problem of alarm effectiveness is one that is seldom addressed. This is evidenced by the lack of regulation or information in the area. The Uniform Building Code (UBC) currently requires fire alarms to have a sound level of 85 dBA at a distance of 10 feet [1]. There are no regulations currently governing multiple occupancy or large building alarm systems from the audibility standpoint. Different buildings have different needs. Not only is the sound level of the alarm important but its directivity and spectral qualities also become significant. Equally critical is the spacing between alarms in a large building.

Other considerations entering into proper alarm system design are the expected background noise level, and the acoustical properties of the structure itself.

Currently all regulations governing location and spacing of alarms are based upon the sensing properties of the detecting units. While an enormous amount of research has been done in the area of location of detectors and detection time, the acoustical effectiveness of the system is seldom quantitatively specified. Only the individual unit loudness is required.

An article in Fire Journal defined the ideal household fire warning system as one that, "1) Provides early warning and maximum coverage of potential fire source areas; 2) is not overly subject to false alarms; 3) is reliable; 4) has a long useful life; 5) is self-supervising; 6) requires little or no maintenance and can be easily tested by the homeowner; 7) can easily be installed in existing buildings and is easily moved within and between buildings; and 8) is low in cost." [2] No mention is made of any audibility criterion at all. If a system met each of the above requirements, yet could not be heard everywhere in the building, it would be ineffective.

What is needed is a comprehensive survey of the acoustical properties of the types of alarms currently on the market. By coupling this data with a computer aided design package, architects and engineers could predict sound levels in a building given its layout, structural materials, and type of alarm systems. In this manner, architects could outfit a building with the alarm system best suited for it. The primary intention of this thesis is to collect data on the acoustical performance of typical alarms.

CHAPTER II

INTRODUCTION

Four alarms currently on the market were chosen to be tested. Two brands of vibrating electric horns, one produced by Pyrotronics and the other by Edwards Corporation, were chosen along with a 10" vibrating bell. A residential smoke alarm was also tested. This choice gave a fairly wide range of alarm types without investing a considerable amount of money. The noise source in the vibrating horn is a metal diaphragm that is made to vibrate by current passing through a solenoid. The bell is simply a shell struck by a clapper. The Edwards alarm is powered by AC current while the Pyrotronic unit uses a direct current power supply and the residential smoke alarm is battery powered. One grill type horn has a plastic projector attachment that can be snapped in place to direct the sound. The other grill type alarm has both a single and double or split metal projector which can direct the alarm in two directions down a hallway. They are attached with metal screws to the horn housing. Figures 1 through 7 show the four basic alarms plus the three projector attachments totalling seven distinct alarm conditions that were tested. The projector attachments were studied to determine if the additional vibrating surface area of the projector enhanced the power output of the grill model of the alarm in addition to modifying its directivity.

The alarm characteristics to be determined are sound power, directivity and frequency spectrum. Sound power and frequency spectrum can be determined in a reverberation room but directivity can only be

measured in an anechoic chamber. An anechoic room is one where nearly 100% of the sound energy is absorbed and simulates a large open field or free field environment. In contrast, an ideal reverberation room is one where very little sound is absorbed and the energy diffuses such that the intensity level is the same at all points in the room. This is called a diffuse field environment. Both anechoic and reverberant rooms were used to determine and compare the characteristics of the alarms.

In order to make the reverberant measurements, it was first necessary to evaluate the performance of a 16,000 ft^3 (453 m^3) handball court as a reverberation room and to design and construct a portable rotating diffuser. The opening chapter of this report describes the method used to evaluate the acoustical properties of the handball court. This is followed by a chapter describing the design and construction of the diffuser. The next chapter in the body of the report describes the measurement techniques employed both in the reverberant room and the anechoic chamber. A concluding chapter summarizes the results and makes recommendations for further work in the area. The appendices contain acoustical measurement data sheets and supporting data.

CHAPTER III

REVERBERANT ROOM EVALUATION

A. General

The determination of sound power emitted by a source in a reverberation room is based upon the premise that under steady state conditions, the squared sound pressure, when averaged in space and time throughout the room, is directly proportional to the power output of the source and inversely proportional to the total absorption in the room [3]. This premise assumes that the sound field is sufficiently diffuse at the frequencies of interest and otherwise depends only upon the physical properties of the medium, i.e. the density of air and the velocity of sound.

Probably the best accepted definition of a perfectly diffuse sound field is offered by Beranek [4]: "In a diffuse sound field there is equal probability of energy flow in all directions and random angle of incidence of energy upon the boundaries of the room." This definition applies to an ideal case, however, and never exists in practice. Measurements made in practice must account for departures from the ideal case. The most common deviation is the existence of standing waves at room resonant frequencies. With a perfectly diffuse field, only one measurement of sound pressure level is necessary in order to exactly determine the power level of a source. Generally speaking, the less diffuse the room, the more variable the sound field; therefore, the more measurements must be made in order to accurately determine sound power.

There are many ways suggested to improve diffuseness in a reverberant room. Among them are making the room large compared to the

wavelength of sound, splaying the walls so that no two are parallel, designing the room size to certain proportions, adding low frequency absorption, and employing both stationary and moving panels [5]. The nature of the room used for this thesis prohibited exercising most of these options. Lack of diffuseness is evidenced by a nonuniform sound field which occurs most often at the low frequencies. This is because at the low frequencies, there are only a few room resonance modes in a particular frequency band width. As the frequency increases, so does the number of modes in each measurement band width which creates greater randomness and makes the sound field more diffuse. Previous research by Schultz [5] has suggested that 10-20 modes are needed for adequate diffuseness. The number of modes in a band width depends upon the room volume, the frequency and the band width itself. The reverberant room used for this study has a volume of 453 m^3 which implies sufficient diffuseness down to 68 Hz.

While a large size is advantageous, largeness causes a problem in the area of air absorption. In reverberant rooms exceeding 283 m^3 the actual absorption of sound by the air enroute to a room boundary becomes a significant factor [5]. This factor is accounted for later in the chapter.

B. Room Evaluation Procedure

In the absence of a qualified reverberation room, a University of Notre Dame handball court was used. It was necessary to test the acoustic response of the room in order to estimate its accuracy. This was done by measuring sound power in the reverberation room by two independent methods. The results were then compared. The handball

court measures 40 feet long by 20 feet wide by 20 feet high. The surface area in the room totals 4000 square feet (371.8 m^3) while the room volume is 16,000 cubic feet (453.0 m^3). Figure 8 shows a drawing of the room. The walls and ceiling are plaster while the floor is hardwood. There is a small wooden access door and plexiglass window on one end wall.

1. Calculation of Room Properties

The first procedure was to estimate the average Sabine absorption coefficient, α_{SAB}, for the room using values obtained from handbooks. Several handbooks [6,7,8] were consulted and the values averaged for each room surface material at each of 8 octave bands with center frequencies ranging from 125 Hz to 8000 Hz. This information is shown in Table 1.

TABLE 1

AVERAGE ABSORPTION COEFFICIENTS*

Frequency	Plaster	Wood	Glass
63	0.015	0.18	0.45
125	0.013	0.15	0.35
250	0.015	0.11	0.25
500	0.02	0.10	0.18
1000	0.03	0.07	0.12
2000	0.04	0.06	0.07
4000	0.05	0.07	0.04
8000	0.06	0.06	0.03

*Coef. at 63 Hz and 8000 Hz are estimated since no handbook values are available.

Using the values from Table 1, the average Sabine absorption coefficient $\bar{\alpha}_{SAB}$ for the room at each frequency can be computed using the following relation given by Magrab [6]:

$$\bar{\alpha}_{SAB} = \frac{1}{S} \sum_{i=1}^{n} S_i \, (\alpha_{SAB})_i \qquad (1)$$

where

$\bar{\alpha}_{SAB}$ = average Sabine absorption coefficient

$(\alpha_{SAB})_i$ = Sabine absorption coefficient of material i

S_i = surface area covered by material i

S = total surface of the room

The resulting average Sabine absorption coefficients are listed in Table 2.

TABLE 2

AVERAGE SABINE ABSORPTION COEFFICIENT $\bar{\alpha}_{SAB}$

	Octave Band Center Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
$\bar{\alpha}_{SAB}$	0.049	0.041	0.034	0.036	0.038	0.044	0.054	0.06

The next step was to use these values to compute the room constant (R) for the room. The room constant [6] is defined by Magrab [6]:

$$R = S\bar{\alpha}_{SAB} + 4mV \qquad (2)$$

where

V = room volume

m = energy attenuation constant.

The term 4mV takes into account sound absorption due to the air in the room. Harris [9] has shown that for frequencies above 1000 Hz, air absorption has a substantial effect on the overall room absorption and this affect varies with temperature and relative humidity. Table A-1 shows how the constant 4m varies with temperature, relative humidity and frequency. The temperature in the room during the experiments was 71 ^{o}F and the relative humidity was 72%. Using Eq. 2 the room constant was calculated for the handball court for each octave band center frequency from 63 Hz to 8000 Hz. These values are tabulated in Table 3.

TABLE 3

HANDBALL COURT ROOM CONSTANTS

	Octave Band Center Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
R(ft^2)	196	164	136	144	152	218	320	534

2. Reference Source Method

Having estimated the room constant for each frequency, a calibrated reference sound source was used to test the room. An ILG model 181-012ZA calibrated sound source was placed in the room and turned on. Octave band sound pressure levels were measured at each frequency from 63 Hz to 8000 Hz from three microphone positions. Figure B-1 shows a sketch of the room layout. The calibrated source was recorded on cassette tape at all three microphone positions. Having measured the sound pressure levels (SPL) in the reverberation room, it was now possible to compare these measured values of sound pressure level,

against the values calculated from the known power level of the source and the room characteristics using the following equation given by Deihl [7]:

$$SPL = PWL + 10Log_{10}\left[\frac{Q}{4\pi r^2} + \frac{4}{R}\right] + 10.3 \qquad (3)$$

where

SPL = sound pressure level in decibels re. 2.0×10^{-5} N/M^2

PWL = sound power level in decibels re. 10^{-12}W

r = distance from source to receiver in feet

Q = Directivity Index = 2.

The Directivity Factor, Q, is defined by Deihl [7] as the ratio of the sound pressure squared, at some fixed distance and specified direction, to the mean squared pressure averaged over all directions at the same distance from the source. For a source suspended in air, $Q = 1$ if the source radiates power equally in all directions. For a source placed on a hard reflecting surface such as the floor of a reverberant room, $Q = 2$.

By entering the calibrated source power level (PWL),the room constant, R, and the microphone distance, r, one can calculate what the SPL should be at each frequency band of interest. Then, by comparing the calculated value to the level actually measured, the relative response of the room in terms of diffusion can be evaluated. Table 4 shows a summary of the results of this method averaged over the three microphone positions.

TABLE 4

AVERAGE SPL (dB) MEASURED VS. CALCULATED FOR ILG SOURCE USING EQ. 3

	Octave Band Center Frequency (Hz)									
	63	125	250	500	1000	2000	4000	8000	Overall	dBA
Measured SPL	67.5	72.2	73.2	73.1	73.9	73.5	71.1	62.2	81.0	79.3
Calculated SPL	69.8	71.1	72.9	73.6	73.4	72.4	69.4	65.5	80.7	78.6

3. Reverberation Time Method

The second method used to evaluate the room response involves the room reverberation time, T. Brach [10] established the reverberation times for this room in earlier experiments by firing a pistol in the room, recording the signal, and measuring the decay rate. These times are listed in TABLE 5.

TABLE 5

REVERBERATION TIMES FOR HANDBALL COURT 4A (SEC)

	Octave Band Center Frequency (Hz)						
	125	250	500	1000	2000	4000	8000
Reverberation Time (Sec)	7.2	4.3	3.9	5.4	5.8	3.9	2.0

The sound pressure level was then calculated using the following equation [7]:

$$SPL = PWL - 10\mathrm{Log}_{10} V + 10\mathrm{Log}_{10} T + 29.5 \qquad (4)$$

where

V = room volume in ft^3

T = reverberation time in seconds.

This method is independent of the room constant (R) which is derived from handbook values. Therefore it is subject only to experimental error. The measured and calculated SPL's were again compared in each octave frequency band and these results are shown in Table 6.

TABLE 6

AVERAGE SPL (dB) MEASURED VS. CALCULATED FOR ILG SOURCE USING REVERBERATION TIMES

	Octave Band Center Frequency (Hz)								
	125	250	500	1000	2000	4000	8000	Overall	dBA
Measured SPL	72.2	73.2	73.1	73.9	73.5	71.1	62.2	81.0	79.3
Calculated SPL	73.1	71.8	72.4	73.8	74.6	71.4	67.0	81.0	79.7

In comparing the calculated and measured values of sound pressure levels from the ILG source, it appears from Tables 4 and 6 that the handball court simulates a reverberant room very well between 125 Hz and 4000 Hz. The largest difference between the measured values and calculated values occurred at 4000 Hz and measured only 1.8 dB. The average difference between 125 Hz and 4000 Hz was only 0.9 dB for the room constant method and 0.8 dB for the reverberation time method. The measured values at 500 Hz and 1000 Hz were exceptionally accurate using both methods with the largest difference being 0.7 dB.

4. Measurement Error

There are three sources of uncertainty in making sound

measurements: instrument accuracy, human error, and source variability. The calibration accuracy of the ILG sound source between 125 Hz and 4000 Hz is $\pm$ 1.5 dB [11], and the microphone used is accurate to $\pm$ 0.5 db [12]. Although the meter accuracy of the sound level meter used is $\pm$ 0.4 dB [13], an overall error due to meter deflection inaccuracy and possible error in reading the meter was assumed to be $\pm$ 0.5 dB. Holman [14] has suggested that by combining the squares of all the uncertainties and taking the square root of the sum, we obtain a good estimate of the overall uncertainty of the system. Using this method, the expected uncertainty of the results is $\pm$ 1.7 dB. In light of this expected uncertainty, the performance of the room as a reverberant environment is excellent.

CHAPTER IV

ROTATING DIFFUSER

A. Purpose and Function

A rotating diffuser consists of a large reflecting vane(s) or panel(s) that moves within the reverberant room in some pattern so as to change the apparent shape of the room relative to the source, and constantly redirect the flow of energy. The first known use of the rotating diffuser was in 1914 by Wallace Clement Sabine while measuring wall transmission losses using a pipe organ as a source. His reasoning for the diffuser is quoted by C. E. Ebbing [15]:

> "The intensity varied greatly in different parts of the room due to interference. In order that the average intensity of sound against the partition in a series of observations should equal the average intensity in the room, it was necessary to continuously shift the interference system. This was accomplished by means of revolving reflectors. This also rendered it possible to obtain a measure of average conditions in the room from observations taken in one position."

Sabine made these points in 1914. Although directed especially towards discrete frequency sound sources, these two points are still critical to precise reverberant room sound measurements. They are more simply put:

1. The use of a rotating diffuser provides a more uniform coupling between the sound source and the receiver room; that is the intensity is more uniformly dispersed and the room is more "diffuse".

2. Use of a diffuser enables fewer measurements to obtain an accurate average sound pressure throughout the room

In the area of 100 Hz to 200 Hz, P. E. Doak [16] has quoted Andres as saying that the sound pressure level in a reverberant field will

display a root mean square deviation from its mean of about 5.5 dB. This means 70% of the measurements will lie in a band 11 dB wide around the mean value if the receiver and source positions are fixed and a rotating diffuser is not employed. Doak also states that fixed diffusers in no way reduce or affect these spatial fluctuations in sound pressure level. By using a rotating diffuser, however, to continuously change the room shape and redirect the energy flow, the fluctuations can be greatly reduced. In light of this need, a rotating diffuser was designed, built, and used for measurements taken in the reverberant room.

B. Design Criteria

There were several criteria affecting the design of the diffuser. The initial constraint was that since measurements were to be made in a handball court, the diffuser had to be portable. T. J. Schultz [5] has shown that the vane must be large enough to reflect the low frequencies well and for the lower cutoff frequency of the 125 Hz octave band, this requires a vane dimension of 12 ft. The vane must also be heavy enough to reflect this frequency. This requires a minimum density of 1 lb/ft^2.

The vane(s) should be oriented so as to intercept as many room modes as possible, which means it should be neither horizontal nor vertical as this would have little effect on the opposite modes. The panel(s) should be nonsymmetric if possible. This is because symmetric shapes tend to cause microphone pressure fluctuations periodic with its rotation. Several unsymmetric panels will produce smaller fluctuations at a much faster pace and will have less of an effect on the microphone signal.

Two additional design parameters are: 1) since the power source must be located within the room, it must be so designed that the diffusers own noise level will not affect the measuring procedure, and 2) it should be so designed as to permit easy access around it in the room in order to prevent injury.

Figure 9 shows a sketch of the diffuser. The design included removable panels so that it could be dismantled easily and carried in and out of the room's 3 ft. by 4 ft. access door. The panel orientation can be varied by adjusting the chains attached to the center shaft. Two nonsymmetric panels were chosen to minimize microphone fluctuations, balance the shaft, and be reasonably easy to transport.

C. E. Ebbing [15] has suggested that a diffuser has its greatest effect (i.e. breaks up the modes in the room best) when rotating at 28-30 RPM. For this reason, a single phase 1/2 Hp constant speed Reliance motor (model AD56) was chosen to drive the diffuser. Since this motor operates at 1725 RPM, a 25 to 1 reducer was employed with a 2.6 to 6 pulley ratio in order to achieve 30 RPM at the output shaft.

C. Construction

The panels were made of 3/8" particle board since its density of 1.3 lb/ft^2 met the weight requirement, yet it was easily constructed and transported. The connecting chain was 1/16" diameter cut to 4 ft. lengths and marked every foot for easy adjustment. A four foot length of 3" channel iron was welded to a hub and mounted by set screws at the base of the output shaft to support the panels. The motor housing was constructed of 3/4" particle board and measured 28" by 24" by 13". The motor was attached to one end of the box using 1/2" threaded rod while

the reducer was bolted to the top of the box using four 1/2" machine bolts. The box was completely lined with several inches of fiberglass insulation to dampen the noise. A 3/4" diameter steel rod extended 4 feet up from the hub and was used to attach the chains to the panels.

Upon testing the diffuser for stability, it was discovered that the motor developed a large starting torque which tended to spin the motor housing on the floor. To solve this, a wooden frame was designed to hold the box and give it added stability. Rubber isolation pads were mounted on both the box and the frame to cushion any vibration. Figure 10 shows a picture of the diffuser assembled in the reverberation room.

CHAPTER V

EXPERIMENTAL MEASUREMENTS AND DATA

A. Instrumentation and Accuracy Estimate

1. Reverberant Environment

All measurements recorded in the reverberant room were measured using a Brüel and Kjaer Model 3503/S Portable Sound and Vibration Instrumentation System. This included a B&K Model 2204 Precision Sound Level Meter, a Model 1613 Octave Band Filter Set, a Model 4220 Pistonphone Calibrator, and a Model 4134, 1/2" Condenser Microphone. All measurements were recorded for later analysis using a Sony TC-160 Stereo Cassette Tape Deck. Frequency spectral analysis was accomplished using a B&K Model 2112 Audio Frequency Spectrometer to obtain 1/1 octave and 1/3 octave band measurements. Several spectral analyses were obtained using a B&K Model 2107 Constant Percentage Bandwidth Frequency Analyzer with attached Model 2305 Level Recorder.

2. Anechoic Environment

All measurements in the anechoic room were carried out using a B&K Model 4145, 1" diameter Condenser Microphone connected to a B&K Model 2131 Digital Frequency Analyzer with video display. Chart recordings were obtained from a B&K Model 2307 Level Recorder. No tape recordings were made of the anechoic room measurements as all readings were recorded on paper immediately.

3. Accuracy Estimate

Both of the microphones used in these experiments have an accuracy to $\pm$ 0.5 dB over the frequency ranges concerned. Each of the three analyzers are accurate to $\pm$ 0.4 dB or better. The alarm source

output levels were not as steady as the ILG source and caused a significant variation in the measurements. Figure 11 shows each of the four source alarms plotted versus time in an effort to illustrate the signal variability. The signals vary from a $\pm$ 2 dB maximum for the Horn #1 Grill Alarm to a $\pm$ 4 dB for the smoke alarm. Care must be taken when measuring time variability of a source in this manner to insure that the recorder writing speed is set properly. If the writing speed is too slow, the pen will not follow the signal accurately and the recording will appear more continuous than it actually is. If the writing speedis too fast the pen will overshoot and the recording will show more variability in the signal than actually exists. A stable writing speed depends upon choosing the damping of the writing system to correspond with the averaging time of rectifier which reads the signal. The writing speed chosen was 315 mm/sec, in accordance with the recorder instruction manual [20], to obtain the closest approximation of signal variability without causing the writing system to overshoot.

Holman's method [14] for computing the overall accuracy of the system gives an overall uncertainty of $\pm$ 2.1 dB for the Horn #1 Grill Alarm, $\pm$ 3.1 dB for the Bell Alarm and the Horn #2, and $\pm$ 4.1 dB for the Smoke Alarm. If the calibrated ILG source is used to determine sound power of the alarms, an added uncertainty is involved. The accuracy limits for the ILG source indicate an uncertainty of $\pm$ 0.5 dB from 125 Hz to 4000 Hz and $\pm$ 1.5 dB at 63 Hz and 8000 Hz. An additional $\pm$ 1 dB tolerance is required since each individual unit is not calibrated [11]. Table 7 shows the uncertainty involved when using the ILG Calibrated Source.

TABLE 7

UNCERTAINTY LIMITS IF ILG SOURCE IS USED

	63 Hz	125-4000 Hz	8000 Hz
Horn #1 Grill Alarm	± 2.8 dB	± 2.4	± 2.8
Horn #2 Grill Alarm	± 3.6	± 3.3	± 3.6
Bell Alarm	± 3.6	± 3.3	± 3.6
Smoke Alarm	± 4.4	± 4.2	± 4.4

B. Reverberant Room Methods

1. Measurements

Having previously evaluated the reverberant room through the use of the ILG source as satisfactory, the room was then set up to measure the sound power of the alarms. Figure B-2 shows that the layout of the room was very similar to Fig. B-1 with the addition of the diffuser. The ambient sound level in the room was measured and recorded in 1/1 octave bands from microphone position 2. Then the diffuser was started and the measurements repeated in order to measure the noise output of the diffuser alone. The results are shown in Table 8.

TABLE 8

AMBIENT SOUND PRESSURE LEVELS (dB)
WITH AND WITHOUT ROTATING DIFFUSER

	Octave Band Center Frequency									
	63	125	250	500	1000	2000	4000	8000	Overall Linear	dBA
Ambient SPL	37.0	36.0	33.0	33.0	22.0	22.0	21.0	21.0	41.0	32.0
Diffuser SPL	65.0	87.0	72.0	63.0	59.0	51.5	47.0	30.0	87.5	71.0

It is obvious from the table that the diffuser produces significant sound levels, particularly in the 125 Hz octave band. Since this could substantially affect the accuracy of the alarm measurements, the diffuser was measured from each microphone position so that the measurements of the alarm levels could be corrected. Four distinct fire alarms along with the three projector attachments were tested for a total of seven different experimental conditions. First, the sound level meter was calibrated to 124 dB using the Pistonphone. Each alarm condition and the diffuser were recorded for 90 seconds at each of the three microphone positions on cassette tape for later laboratory analysis.

2. Analysis

(a) <u>Sound Power</u>: The second power of the alarms was calculated by three methods. First, Eq. 3 was implemented using the Room Constant (R) calculated earlier. Secondly, the sound power was calculated using the reverberation time in Eq. 4. Finally, the sound power was obtained using a comparison method with the calibrated reference source.

Equation 5 shows Eq. 3 rearranged to solve for the sound power level (PWL) given the sound pressure level (SPL):

$$PWL = SPL - 10\log_{10}\left(\frac{2}{4\pi r^2} + \frac{4}{R}\right) - 10.3 \qquad (5)$$

The recorded signals were fed into the Audio Frequency Spectrometer to obtain the sound pressure levels at each octave band for each microphone position. These sound pressure levels were entered into Eq. 5 along with the appropriate values for the room constant (R) and receiver distance (r) and the corresponding sound power levels were calculated. These sound power levels were averaged over the microphone positions to obtain an average sound power level for each alarm. Table 9 summarizes the results.

TABLE 9

AVERAGE SOUND POWER LEVELS (dB) CALCULATED USING THE ESTIMATED ROOM CONSTANT (R)

Center Frequency	Horn #1 Grill Alarm	Horn #1 with Projector	Horn #2 Grill Alarm	Horn #2 with Single Projector	Horn #2 with Double Projector	Bell Alarm	Smoke Alarm
63	67.9	68.3	60.5	67.4	61.8	64.1	59.3
125	84.4	82.4	78.7	85.8	83.6	86.7	80.2
250	82.0	84.7	85.6	81.3	82.8	72.6	72.7
500	89.3	92.6	90.7	99.7	98.1	75.4	68.8
1000	101.6	104.6	100.2	100.9	99.3	87.3	71.7
2000	111.5	112.1	102.7	105.4	106.9	95.9	94.3
4000	107.6	107.6	96.1	97.2	98.4	106.9	92.0
8000	99.7	100.5	88.9	89.0	89.8	105.5	79.9
Overall	113.5	114.2	105.5	108.3	108.6	109.3	96.6
dBA	114.5	115.1	106.2	108.4	109.3	109.7	97.5

The Horn #1 Alarm was the loudest of the brands tested with an overall A-weighted sound power level of 114.5 dBA while the Smoke Alarm was the quietest with a sound power level of only 97.5 dBA. The addition of the projectors raised the level of the grill type alarms in all three cases. This is especially true for the Horn #2 alarm whose level jumped over 3 dB with the projector while the Horn #1 Projector raised the level of its grill model by only 0.7 dB. This result could be due to the attachment hardware since the Horn #2 projectors are screwed on while the Horn #1 Projector is only slipped into position.

The second method for calculating the sound power of the alarms utilized the room reverberation time and the room volume. Equation 4 is rewritten in the following manner:

$$PWL = SPL + 10\mathrm{Log}_{10} V - 10\mathrm{Log}_{10}\ T - 29.5 \qquad (6)$$

By entering the room volume, this reduces to:

$$PWL = SPL - 10\mathrm{Log}_{10}\ T + 12.54 \qquad (7)$$

The sound pressure levels obtained from the recording were combined with the appropriate reverberation times from Table 5 to give the sound power levels for each octave band from each microphone position. The results were averaged over the three microphone positions and are shown in Table 10.

The final calculation was made using the known power output of the ILG Calibrated source. In reverberation rooms, Schultz [3], has shown that given a source of known sound pressure level (SPL) and a calibrated noise whose sound pressure level and sound power level are both known, then the sound power level of the unknown source is simply

TABLE 10

SOUND POWER LEVELS (dB) CALCULATED USING ROOM REVERBERATION TIMES

Center Frequency	Horn #1 Grill Alarm	Horn #1 with Projector	Horn #2 Grill Alarm	Horn #2 with Single Projector	Horn #2 with Double Projector	Bell Alarm	Smoke Alarm
125	82.9	81.0	75.9	73.2	85.0	83.3	78.0
250	83.2	86.1	86.9	83.5	84.0	74.0	73.7
500	90.9	94.2	92.3	100.9	99.1	76.9	70.2
1000	101.6	104.7	99.7	100.9	99.2	87.5	71.4
2000	109.5	110.4	101.0	103.6	105.1	94.1	92.7
4000	106.0	106.1	94.2	95.1	96.0	104.9	90.6
8000	99.1	88.2	87.7	87.8	88.4	104.6	78.9
LIN	111.9	112.6	104.1	107.1	107.3	108.0	95.0
dBA	113.2	113.6	104.8	107.2	107.5	108.1	96.0

given by the formula:

$$PWL_A = PWL_{REF} - \overline{SPL}_A + \overline{SPL}_{REF} \qquad (8)$$

where

PWL_A = sound power level of alarm in decibels re 10^{-12} W

PWL_{REF} = sound power level of reference sound source in decibels

$\overline{SPL}_A$ = average SPL of alarm in decibels re. 2×10^{-5} N/m^2

$\overline{SPL}$ = average SPL of reference sound source in decibels

This assumes that no change in room absorption has occurred between the two sound pressure level measurements. The sound pressure levels for both the alarm and the reference source were averaged over the microphone positions and inserted into Eq. 8 along with the reference source sound power to obtain the sound power of the alarm. These results are shown in Table 11.

The three methods for obtaining sound power gave closely corresponding results. For any given alarm the widest variation between overall readings was 1.7 db. This variation is well within the expected uncertainty limits set forth earlier in this section. The largest variations occurred in the 125 Hz and 8000 Hz octave bands. This was expected in Table 11 since the variability of the ILG source is higher at 8000 Hz, and at 125 Hz, it is known that the sound field is less diffuse. In Table 9, the room constant (R) used in Eq. 3 to calculate the sound power had to be estimated at 8000 Hz since no values were available for this band. Between the 250 Hz and 4000 Hz bands only 4 variations in measured sound power level occurred that were outside the expected uncertainty limits given earlier.

TABLE 11

REVERBERANT ROOM SOUND POWER (dB) CALCULATIONS
ILG COMPARISON METHOD

Center Frequency	Horn #1 Grill Alarm	Horn #1 with Projector	Horn #2 Grill Alarm	Horn #2 with Single Projector	Horn #2 with Double Projector	Bell Alarm	Smoke Alarm
125	83.2	81.9	74.8	84.1	81.2	81.9	77.5
250	81.5	84.7	86.1	82.1	81.8	72.6	72.3
500	90.2	93.5	81.6	100.2	98.8	76.2	69.4
1000	101.4	104.6	99.8	100.8	99.1	87.1	71.1
2000	109.6	111.5	102.0	104.7	106.2	95.2	93.8
4000	106.1	106.4	94.0	95.4	96.3	105.2	90.9
8000	103.5	104.8	92.5	92.6	93.4	109.5	83.6
LIN	112.3	113.9	105.0	107.6	108.1	111.0	96.0
DBA	113.1	114.7	105.5	107.9	108.7	110.6	96.9

(b) Frequency Analysis: Another important characteristic of sound power is its frequency spectrum or how the sound power varies as a function of frequency. This is important in the case of fire alarms because the human ear does not respond equally well to all frequencies. Thus, a given sound level may not be as effective if it is at a frequency that the human ear cannot hear well. Another reason for a frequency analysis is to pinpoint the location of peak sound power within the spectrum. This information is extremely important when predicting sound levels in a room since materials respond differently at different frequencies.

The recorded signals were analyzed by a B&K Model 2107 Constant Percentage Bandwidth Frequency Analyzer and the spectrum was printed on an attached Model 2305 level recorder. Each alarm condition and the diffuser were analyzed for sound pressure level from 20 to 20,000 Hz. These spectra are shown in Fig. 12 through 20.

For the Horn #1 Grill and Projector alarms, shown in Fig. 12 and 13, the sound power is concentrated to a great extent near two frequencies, one around 1100-1200 Hz, and another from 2400 Hz to 3000 Hz. The Horn #1 alarm maintains a sound pressure level above 90 dB from 900 Hz to nearly 9000 Hz. The frequency spectrum for the Horn #2 (see Fig. 14, 15, 16) is very similar to the Horn #1 alarm although its overall level is lower. The Horn #2 alarm reaches a sound pressure level of 90 dB at 500-600 Hz and holds that level to only 3000 Hz. This could be a significant difference since building materials generally transmit sound more effectively at the lower frequencies. The Bell alarm, whose spectrum is shown in Fig. 17, maintains the bulk of

its acoustical energy between 2500 Hz and 12,000 Hz. This spectrum is significantly different from either of the grill type alarms and could be more desirable in different environments. The Smoke Alarm exhibits a much narrower band of power output than the commercial alarms. It reaches a sound pressure level of 80 dB at about 2000 Hz and maintains that level to about 4000 Hz where it drops off quickly.

Figure 19 shows the frequency spectrum of the diffuser itself with most of its sound intensity centered between 100 Hz and 200 Hz. This property of the diffuser is reflected in each alarm's spectrum between 100 and 200 Hz. During the experiment it was possible to find room modes where the diffuser was generating standing waves in the reverberant room. This is evidenced by Fig. 19 and 20 which are frequency spectra of the diffuser measured from two different microphone positions. A difference in peak value of nearly 5 dB was typical of all measurements taken from those two microphone positions at that frequency.

C. Anechoic Room Methods

1. Measurement

Due to limited availability of an anechoic room, only the four distinct source conditions were tested to determine sound power. The grill type alarms fixed with the projector attachments were tested only to determine their directivity characteristics so that fewer measurements would be required. These measurements were important because directivity cannot be measured in a reverberant room. To obtain directivity, an anechoic environment is needed.

Each alarm was placed in the center of the floor on a piece

of foam to avoid vibrating the floor grating. The alarms' sound pressure levels were measured at 45 degree intervals around a horizontal circle at each of four different heights while maintaining a constant radius of four feet from the source. A final measurement was taken at the same radius directly above the alarm for a total of 33 measurements for each alarm. Figure 21 shows a picture of the measurement scheme.

When measuring sound levels in an anechoic room, the microphone must be positioned far enough from the source to insure that it is not in the near field of the source and yet, it must not be too close to the walls of the room since the sound pressure level drops quickly as it nears the absorptive material. Acoustic handbooks [17] suggest that the microphone be positioned no closer to the wall than 1/4 wavelength of the lowest frequency of interest. For the 125 Hz octave band, that minimum distance is 27 inches. The anechoic room measured 13 feet between wedge tips so the radius of measurement was chosen to be 4 feet.

Sound power can be computed from anechoic room measurements using Eq. 5. For an anechoic room, however, the room constant (R) is very large so that the term 4/R becomes very small and can be neglected. This reduces the equation to:

$$PWL = \overline{SPL} - 10\mathrm{Log}_{10}\left[\frac{Q}{4\pi r^2}\right] - 10.3 \qquad (9)$$

The value of the Directivity Factor, Q, is unity in this case and for the specific radius, r=4 feet, Eq. 9 becomes

$$PWL = \overline{SPL} + 13.03 \qquad (10)$$

By inserting the alarm sound pressure levels into Eq. 10, the sound power was calculated and recorded. Table 12 shows a summary of the results.

TABLE 12

ANECHOIC ROOM SOUND POWER (dB)
AVERAGED OVER ALL MICROPHONE POSITIONS

Center Frequency	Horn #1		Horn #2		BELL ALARM		SMOKE ALARM	
	$\overline{SPL}$	PWL	$\overline{SPL}$	PWL	$\overline{SPL}$	PWL	$\overline{SPL}$	PWL
125	58.1	71.1	35.1	48.1	43.4	56.4	31.0	44.0
250	65.2	78.1	56.4	69.4	45.8	58.8	49.1	62.1
500	73.9	87.1	79.5	92.5	63.5	76.5	53.6	66.6
1000	92.7	105.7	91.9	104.9	71.9	84.9	56.3	69.3
2000	96.5	109.5	92.0	105.0	80.3	93.3	74.2	86.8
4000	91.1	104.1	81.1	94.1	91.1	104.1	84.5	97.4
8000	90.4	103.4	78.3	91.3	92.5	105.5	72.4	85.1
16000	-	-	-	-	88.9	101.9	66.9	79.4
Linear dBA.	99.4	112.4	95.4	108.4	96.9	109.9	85.1	98.1

2. Analysis

a. Sound Power: There has long been a perplexing problem concerning the determination of sound power. In a reverberation room at low frequencies, the sound power measured is lower than when it is determined in the free field or anechoic environment for the same source. Three separate theories have attempted to explain this discrepancy. They are: (1) the influence of the room impedance on the measurements, (2) the lack of a sufficient number of normal modes at the low frequencies resulting in an irregular room response, and (3) a measurement error in

calculating the room reverberation time by not using the early decay rate [18]. With this as a background, the alarm measurements made in the anechoic chamber were compared with those made in the handball court. Figures 22 through 25 show the sound power comparison for each of the four alarm source conditions between the anechoic room sound power and that calculated in the reverberant room. Table 13 shows the overall linear values for each alarm and their corresponding A-weighted power levels as determined in both the anechoic chamber and the reverberation room.

TABLE 13

SOUND POWER LEVELS (dB)
ANECHOIC AND REVERBERANT ROOMS

ALARM	Anechoic Room		Reverb.Rm.w/ Room Const.Eq.		Reverb.Room w/ Reverb.Time Eq.		Reverb.Room w/ ILG Comparison	
	Over-all	A-Weighted	Over-all	A-Weighted	Over-all	A-Weighted	Over-all	A-Weighted
Horn #1	112.4	113.1	113.5	114.5	111.9	113.2	112.3	113.1
Horn #2	108.4	108.9	105.5	106.2	104.1	104.8	105.0	105.5
Bell Alarm	109.2	108.2	109.3	109.7	108.0	108.1	111.0	110.6
Smoke Alarm	98.1	98.6	96.6	97.5	95.0	96.0	96.0	96.9

Table 13 and Figs.22 through 25, show that the measurements made in the reverberation room are very consistent but differ from those made in the anechoic chamber. The curves show a characteristic discrepancy at the 125 Hz and 250 Hz octave bands which is attributable

to the noise level of the rotating diffuser. There does not appear to be a pattern to the variations between the anechoic and reverberant measurements at the remaining frequencies.

b. Directivity: Measurements of sound pressure level as a function of angular position in a horizontal plane around each source showed very little variation so only vertical plane directivity was investigated. Using a stationary microphone stand, two measurements 180 degrees apart were taken at each of the height levels used previously for sound power calculation. This measurement scheme revealed a large amount of directivity, especially with the addition of the projector attachments. This data is shown in Figs.26 through 35. No directivity measurements were made on the Smoke Alarm.

The alarms were placed face up on the floor of the room and the microphone passed in one arc from a horizontal position level with the alarm over the top of the alarm down to the same level on the other side. Levels were recorded at 9 positions on this arc. Figure 36 shows a sketch of the measurement scheme. By assuming symmetry in the horizontal plane, only one 180 degree arc was necessary to obtain an accurate estimate of the alarms vertical directivity.

Both the Horn #1 and Horn #2 Grill type alarms showed a sharp variation in power output as themicrophone swept through the angle θ over the top of the alarm. These changes ranged from 3 dB to 10 dB and occurred only in the four higher octave bands. The three lower bands showed higher sound powers at an angle of $\theta = 50$ degrees and $\theta = 130$ degrees. When the projector attachments were fixed on the grill

alarms, the sound power increased much more sharply as the angle θ increased to 90 degrees and then decreased as it moved towards 180 degrees. (See Figs.28, 29, 32, 33). The increases for the projectors ranged between 10 dB and 20 dB. The bell alarm produced much higher power levels on either side of the face of the alarm at angles of $\theta = 0$ degrees and 180 degrees. (See Figs.34, 35). This could be an important consideration for alarms mounted in a long hallway.

Three linear directivity measurements on the Horn #2 Double Projector Alarm were made in the horizontal plane at each of the 4 microphone heights. (By taking 3 measurements from 0° to 90° and assuming symmetry, a good idea of the directivity of the alarm could be obtained). Figure 37 shows a plan view of the measurement scheme with the microphone positions oriented at 0°, 45°, and 90° to the alarm horn. All measurements were made at a radius of 4 feet and the results are plotted in Figs.38 and 39 for each microphone height. There was surprisingly little variation in the horizontal plane between the measurements made at 0° and those at 90° to the horn opening. Microphone position 2 (45°) consistently recorded the lowest level at each height but the total variation between the three measurements never exceeded 2 dB. Examining the vertical plane showed almost no change at all as two measurements taken directly above the alarm were within 1 dB of those taken at the lower levels.

CHAPTER VI

CONCLUSIONS

There are several conclusions to be drawn from this work and, for clarity, this chapter is divided into three sections; one for each objective that was stated in the introduction. They are: data collection, reverberant room evaluation, and rotating diffuser design.

A. Data Collection

This objective of collecting a comprehensive data set on several alarms describing their sound power, directivity and frequency spectra was met. This data not only provides information concerning the acoustical properties of each alarm, but also points out some characteristic differences between alarms which is the crux of aiding the architect or engineer in his work.

The Vibrating Horn #1 recorded an overall sound power level of 112.4 dB (113.1 dBA) in the anechoic room and averaged 112.6 dB (113.6 dBA) in the reverberant room. The Bell Alarm was nearly as loud with an anechoic measure of 108.2 dB (108.0 dBA) and an average of 109.4 4B (109.5 dBA) in the reverberant room. The Vibrating Electric Horn #2 averaged 104.9 dB (105.2 dBA) in the reverberant room and 108.4 dB (108.9 dBA) in the anechoic environment. The Smoke Alarm averaged 95.9 dB (96.8 dBA) in the reverberant room and 98.0 dB (98.6 dBA) in the anechoic room.

The projector attachments were found to modify the directivity sharply. They also significantly raised the power level of the Horn #2 alarm (+3 dB). The projector attachment raised the power level of the Horn #1 Grill alarm by only 0.7 dB.

The Horn #1 and Horn #2 Alarms showed similar power spectral traits. The Horn #1 model held a 90 dB level over the longest frequency span but the Horn #2 model attained that level at a much lower frequency (600 Hz). The Bell Alarm contained its power at frequencies higher than either of the two horns and the Smoke Alarm had a very limited band of power.

B. Reverberant Room Evaluation

The three methods used to determine sound power in the handball court produced results that agreed very well. Variation in overall readings was only 1.7 dB. Except for the measurements affected by the diffuser, only 2.6% of the 1/1 octave measurements made fell outside of the expected uncertainty limits of ± 2.1 dB for the Horn #1 Alarm, ± 3.1 dB for the Horn #2 and the Bell Alarm, and ± 4.1 for the Smoke Alarm. In light of the results above, the use of the handball court as a reverberation room leads to reasonably small errors and is highly successful.

C. Diffuser Design

This objective was also met in that a rotating diffuser was indeed designed, constructed, and used in making the necessary measurements. Its success, however, was somewhat limited due to its own noise level. Some major modifications must be made to this piece of equipment in order for it to perform satisfactorily.

CHAPTER VII

RECOMMENDATIONS

This work is the pilot study for much more research to follow. Several suggestions for future study and improvements to this work are listed below.

1. Expand the data base by including more brands and different types of alarms.

2. Examine the mechanical design of the alarm to determine its natural frequencies and attempt to relate them to the acoustical output.

3. Increase the accuracy of the reverberant room measurement by taking more samples of the alarms in the diffuse field environment.

4. Modify the acoustical diffuser in order to quiet its noise level. Add interior bracing to the diffuser motor housing to reduce the vibration of the wooden sides. If possible, redesign the motor housing to be more stable and eliminate the need for the wooden frame.

5. Qualify the reverberant room using ANSI STD S121-1972.

6. Develop a computer package to couple with this data and establish design techniques for some typical multiple occupancy buildings.

7. Verify the design package experimentally using existing buildings.

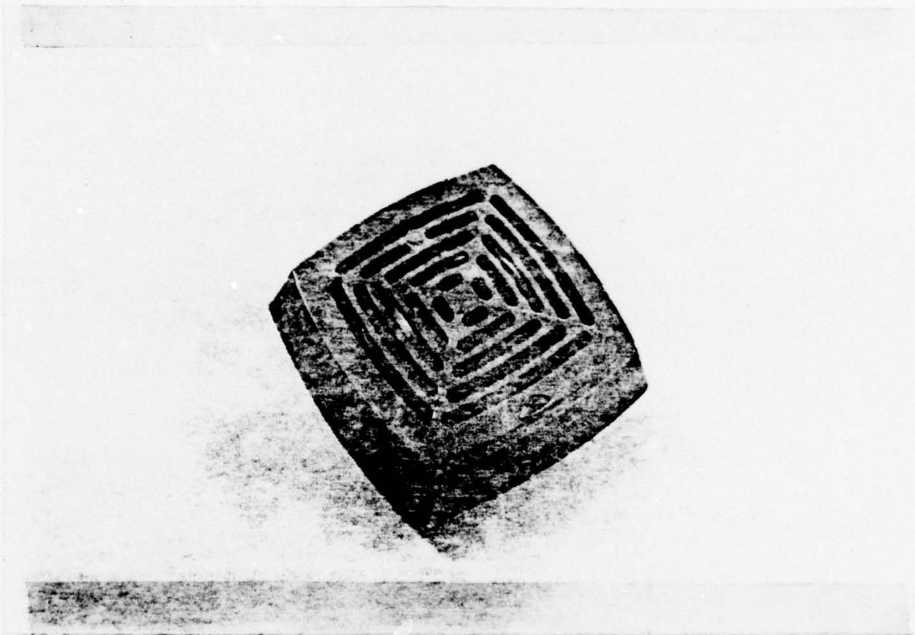


FIGURE 1. Vibrating Electric Horn #1 Grill Alarm.

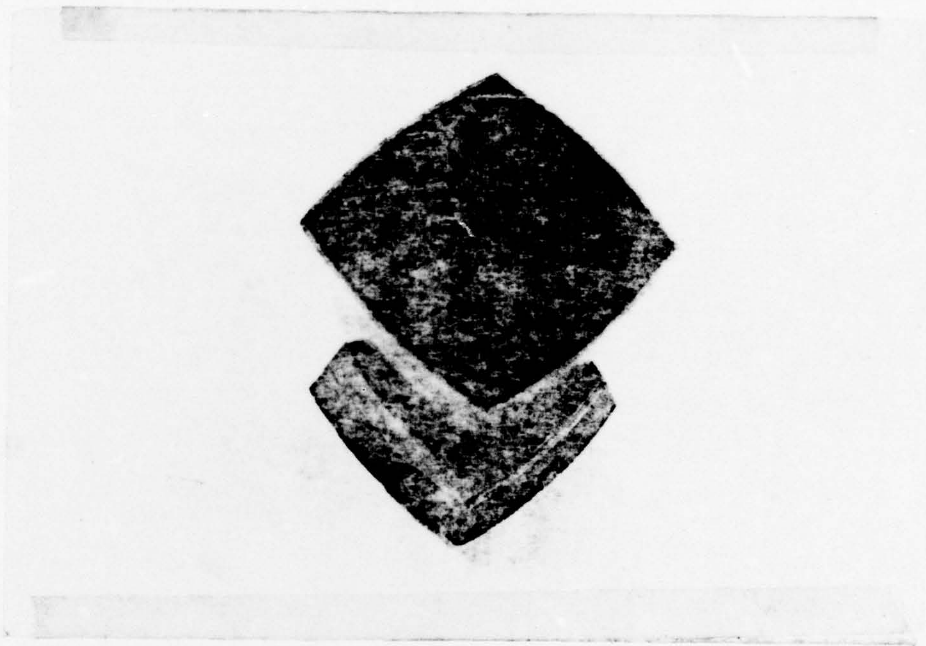


FIGURE 2. Vibrating Electric Horn #1 Grill Alarm with Projector.

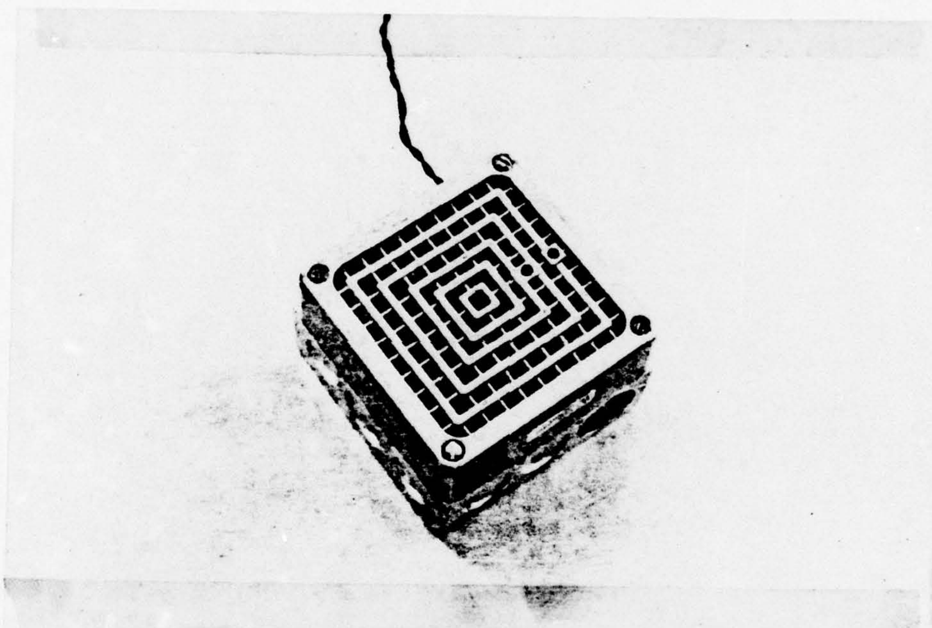


FIGURE 3. Vibrating Electric Horn #2 Grill Alarm.

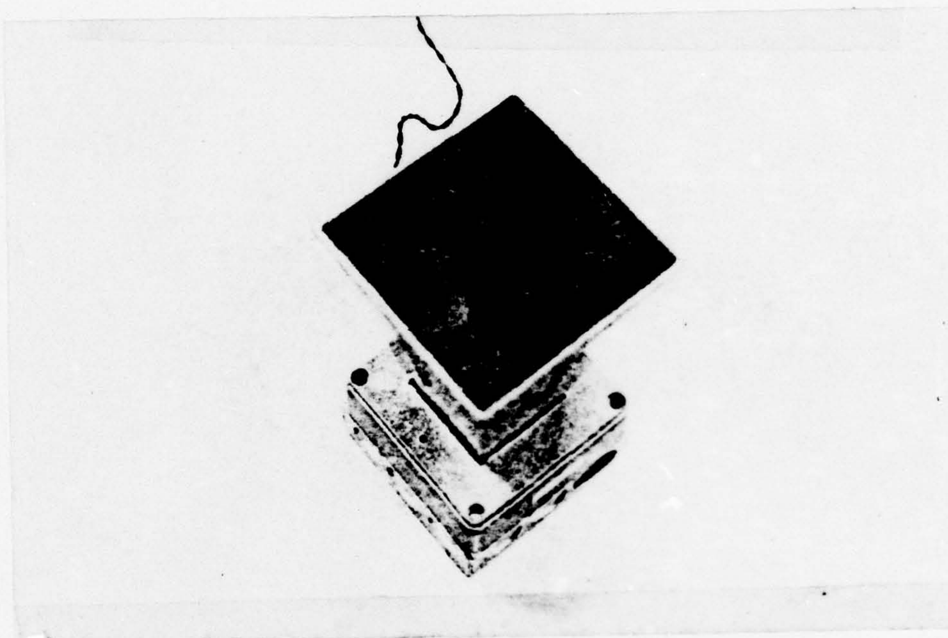


FIGURE 4. Vibrating Electric Horn #2 Grill Alarm with Single Projector.

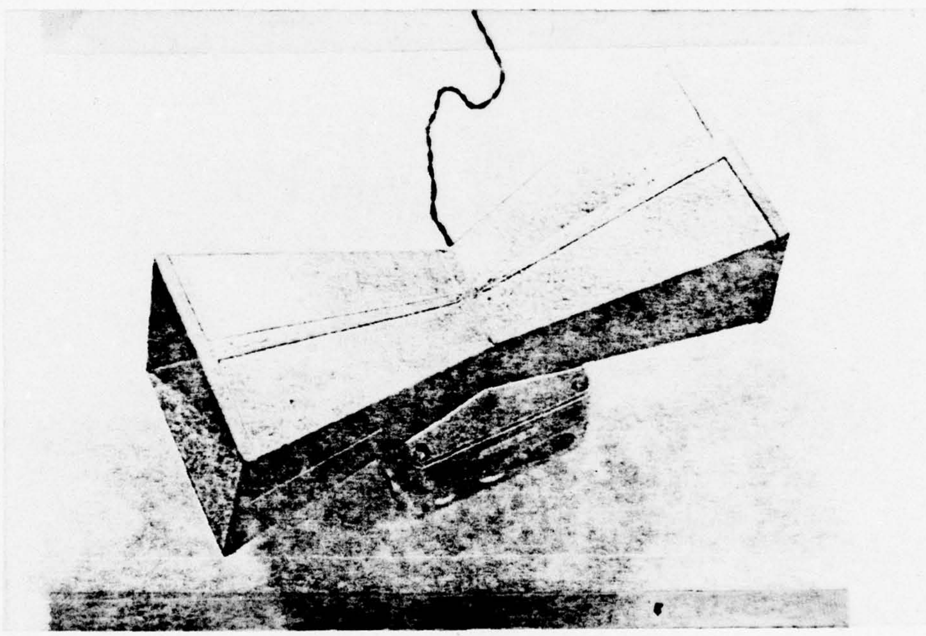


FIGURE 5. Vibrating Electric Horn #2 Grill Alarm with Double Projector.

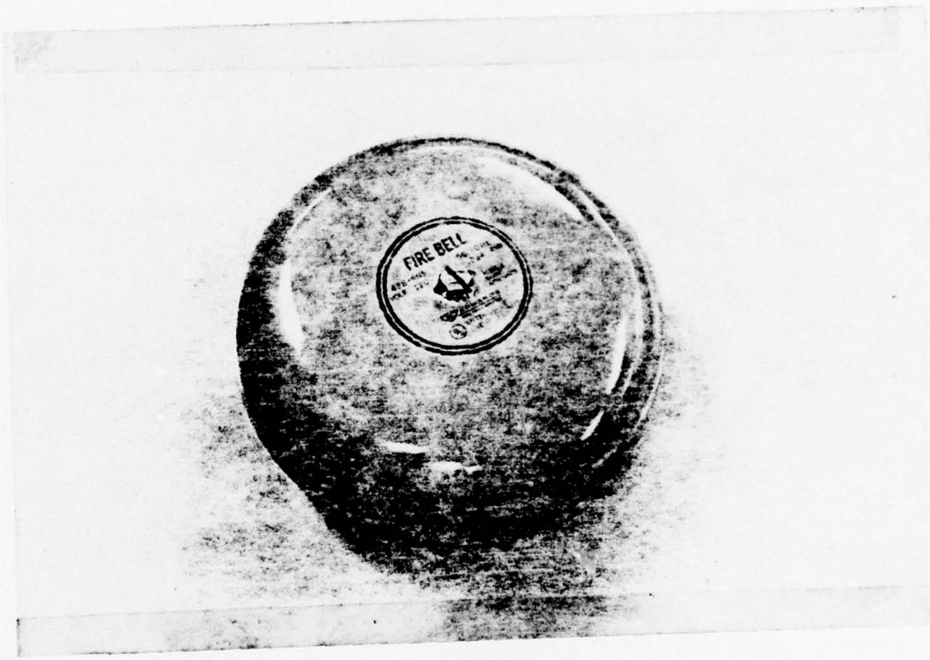


FIGURE 6. Bell Alarm.

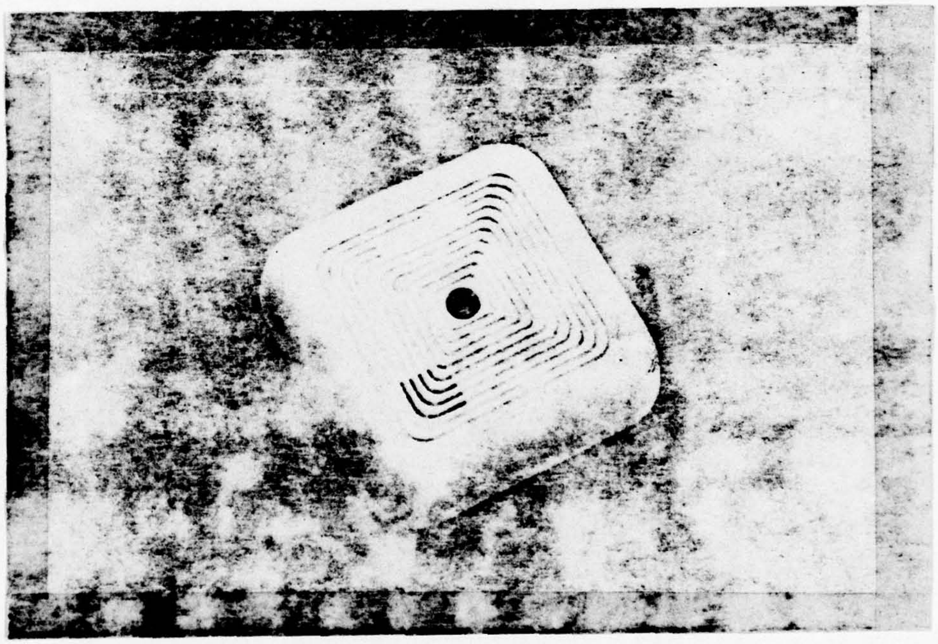


FIGURE 7. Smoke Alarm.

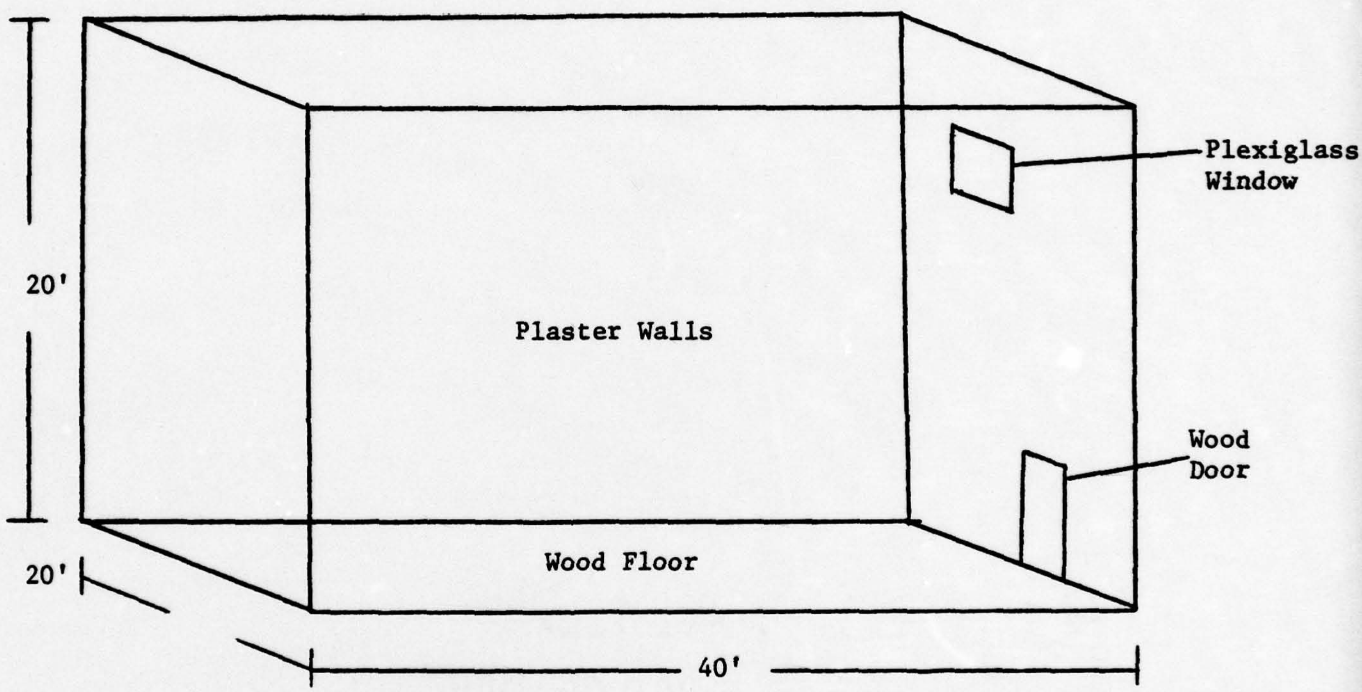
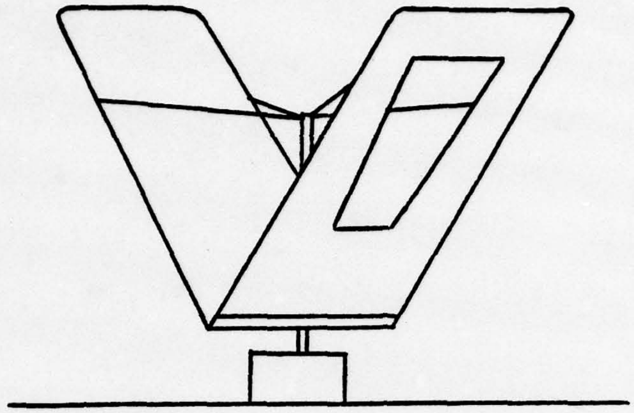
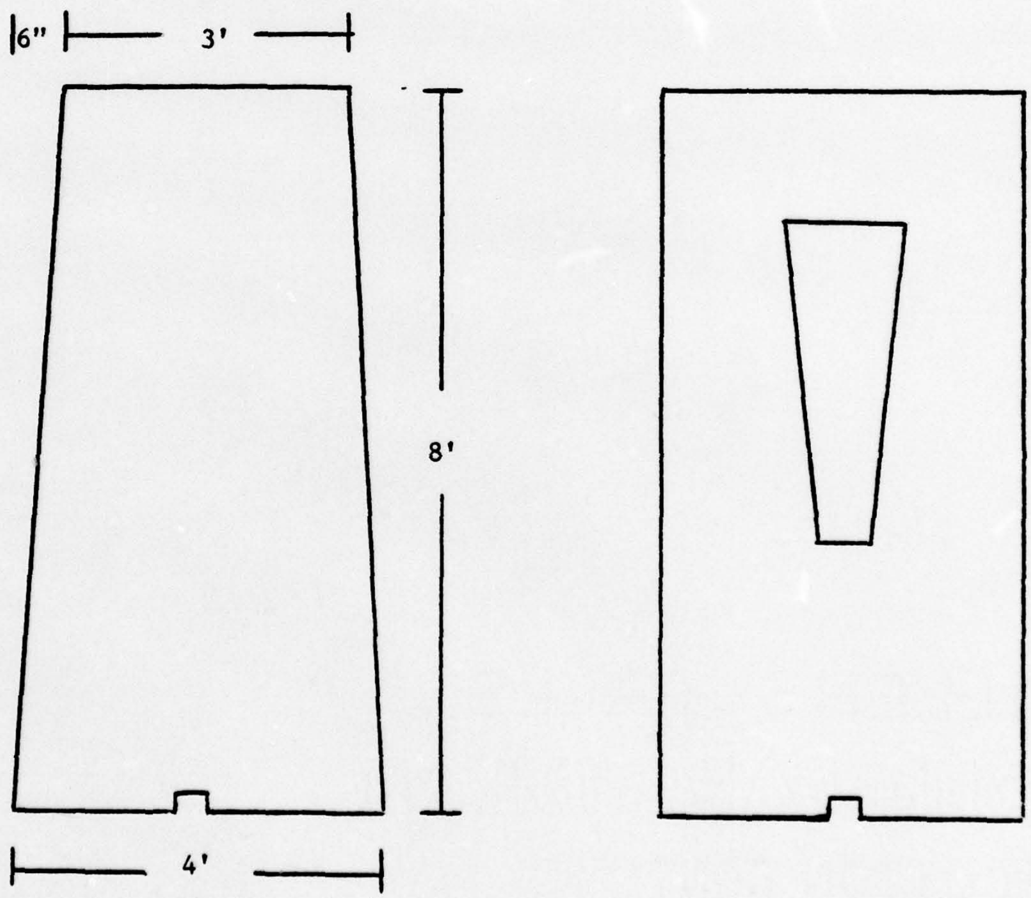


FIGURE 8. Handball Court 4A Athletic and Convocation Center, University of Notre Dame.



a. Overall Diffuser Shape



b. Panel Dimensions

FIGURE 9. Rotating Diffuser.

FIGURE 10. Rotating Diffuser Photo.

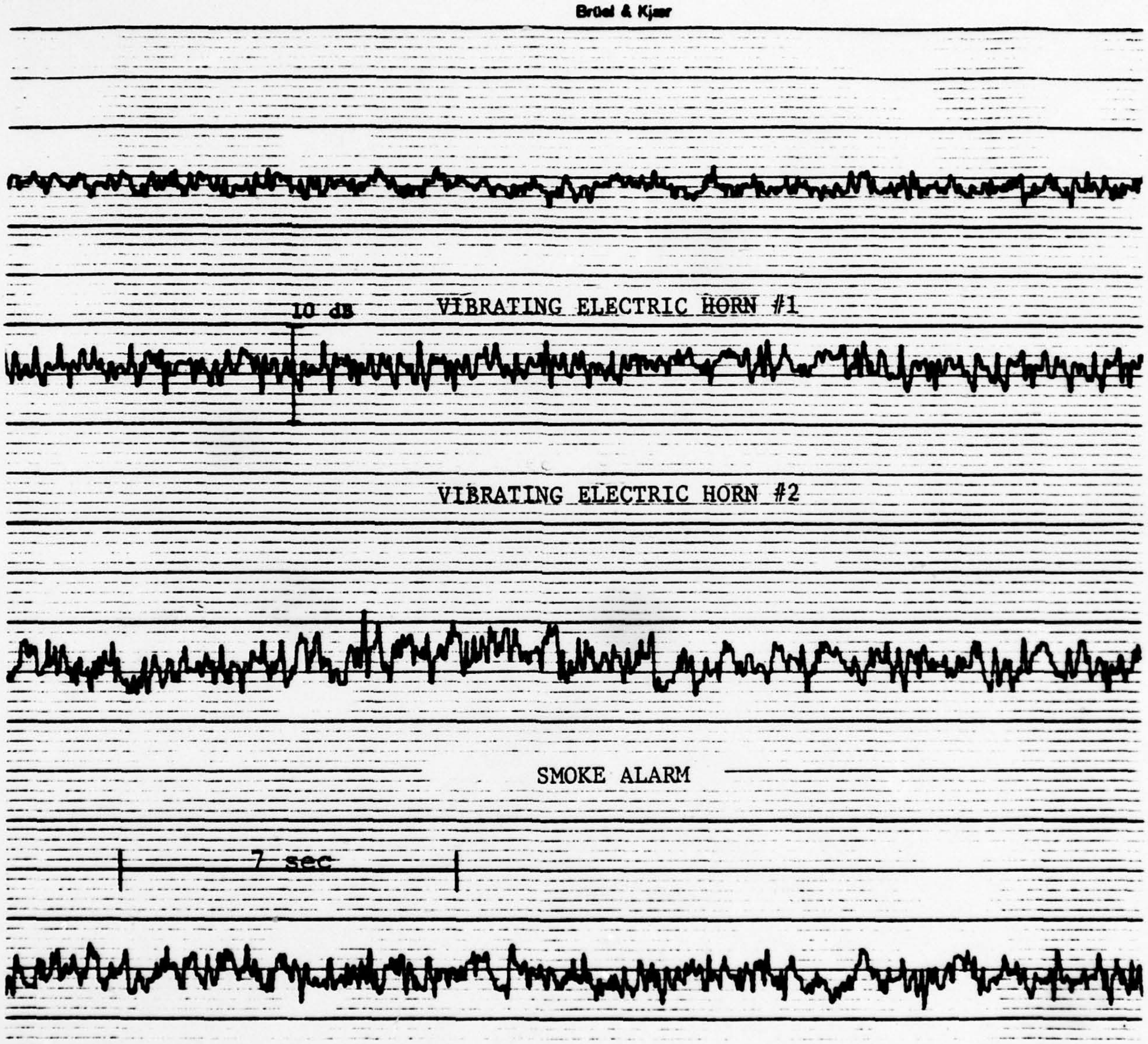


FIGURE 11. Alarm Variability Plotted vs. Time.

FIGURE 12. Frequency Spectrum of Vibrating Electric Horn #1.

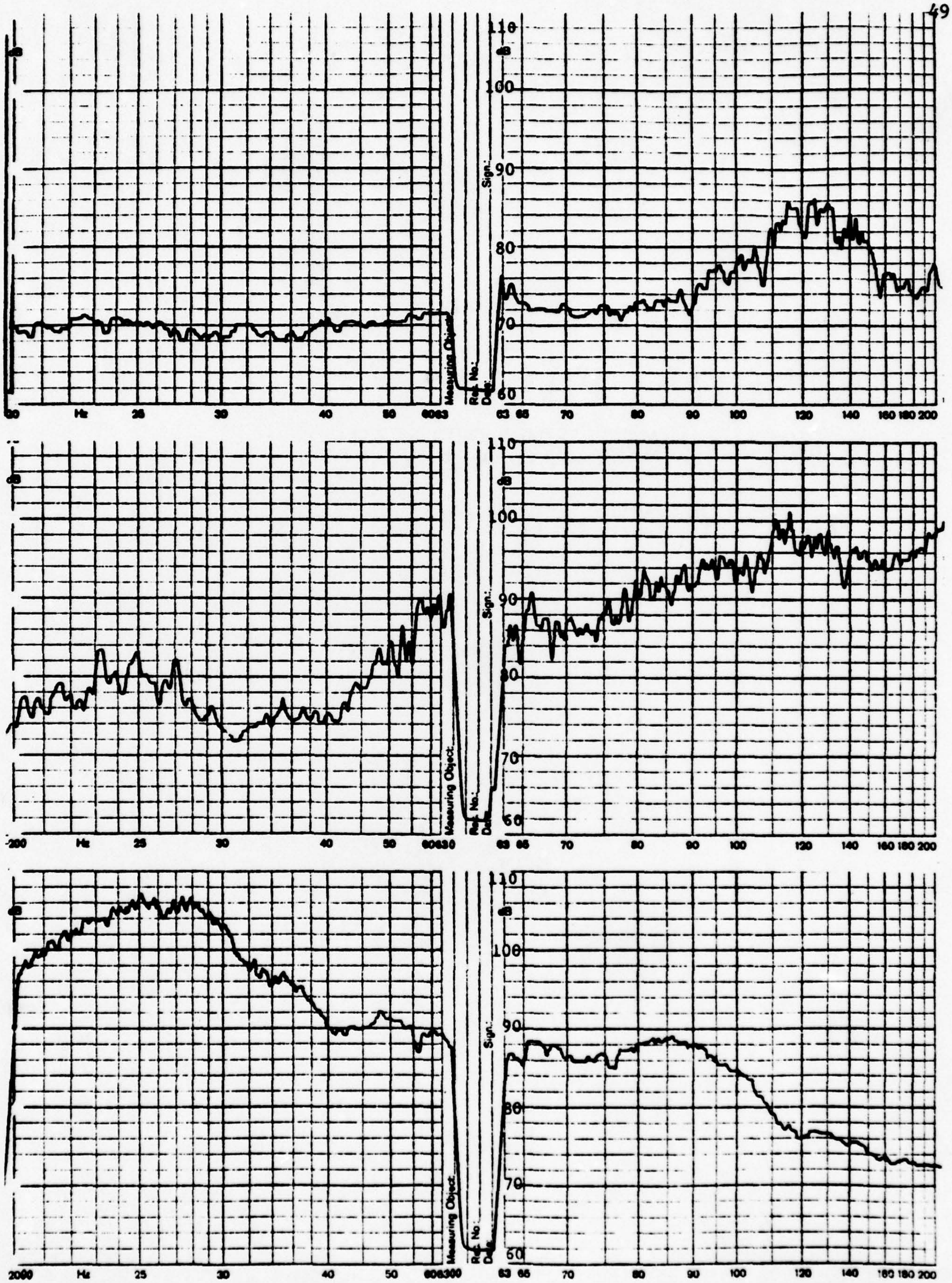


FIGURE 13. Frequency Spectrum of Vibrating Electric Horn #1 Grill Alarm with Projector.

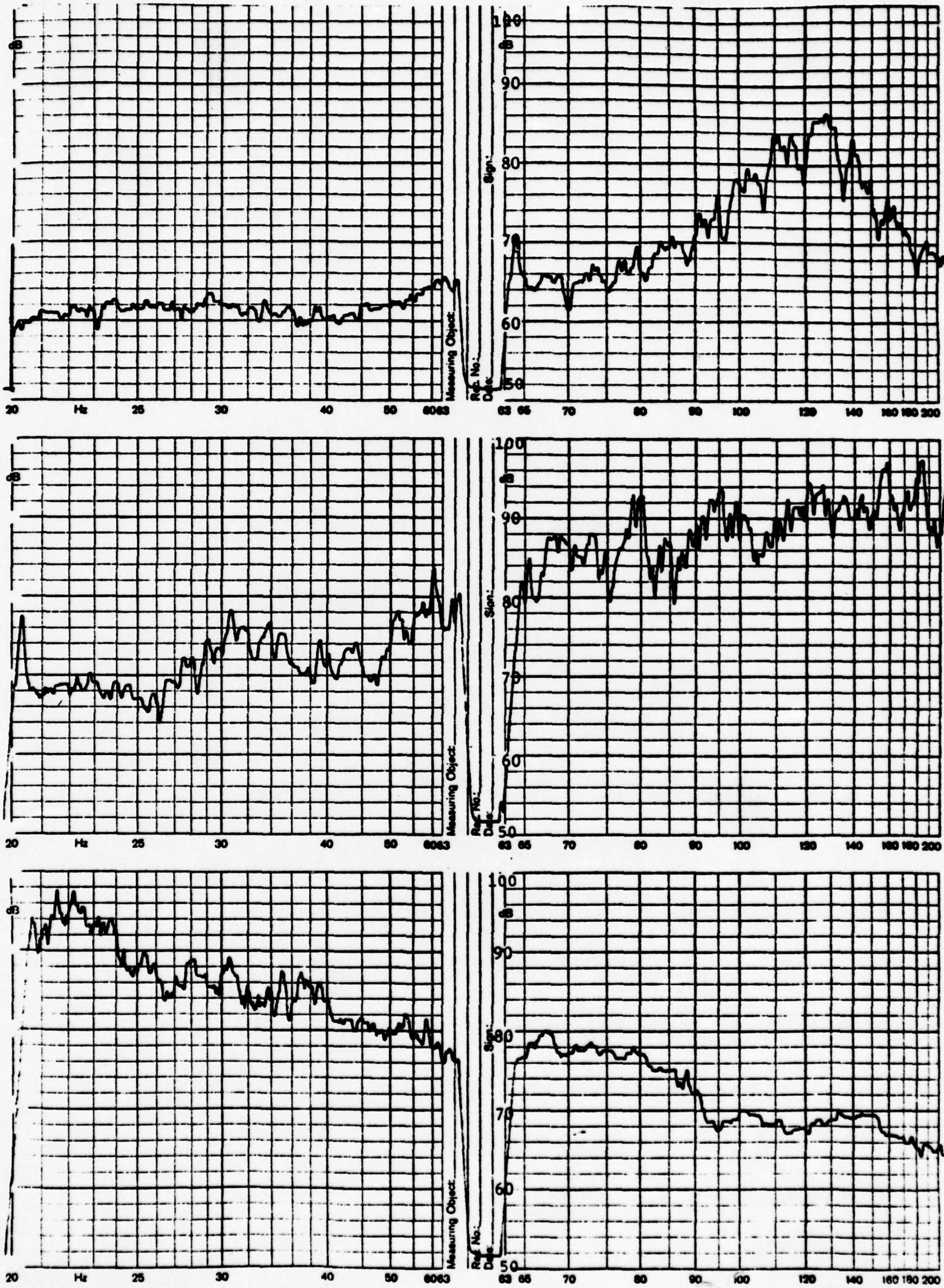


FIGURE 14. Frequency Spectrum of Vibrating Electric Horn #2 Grill Alarm.

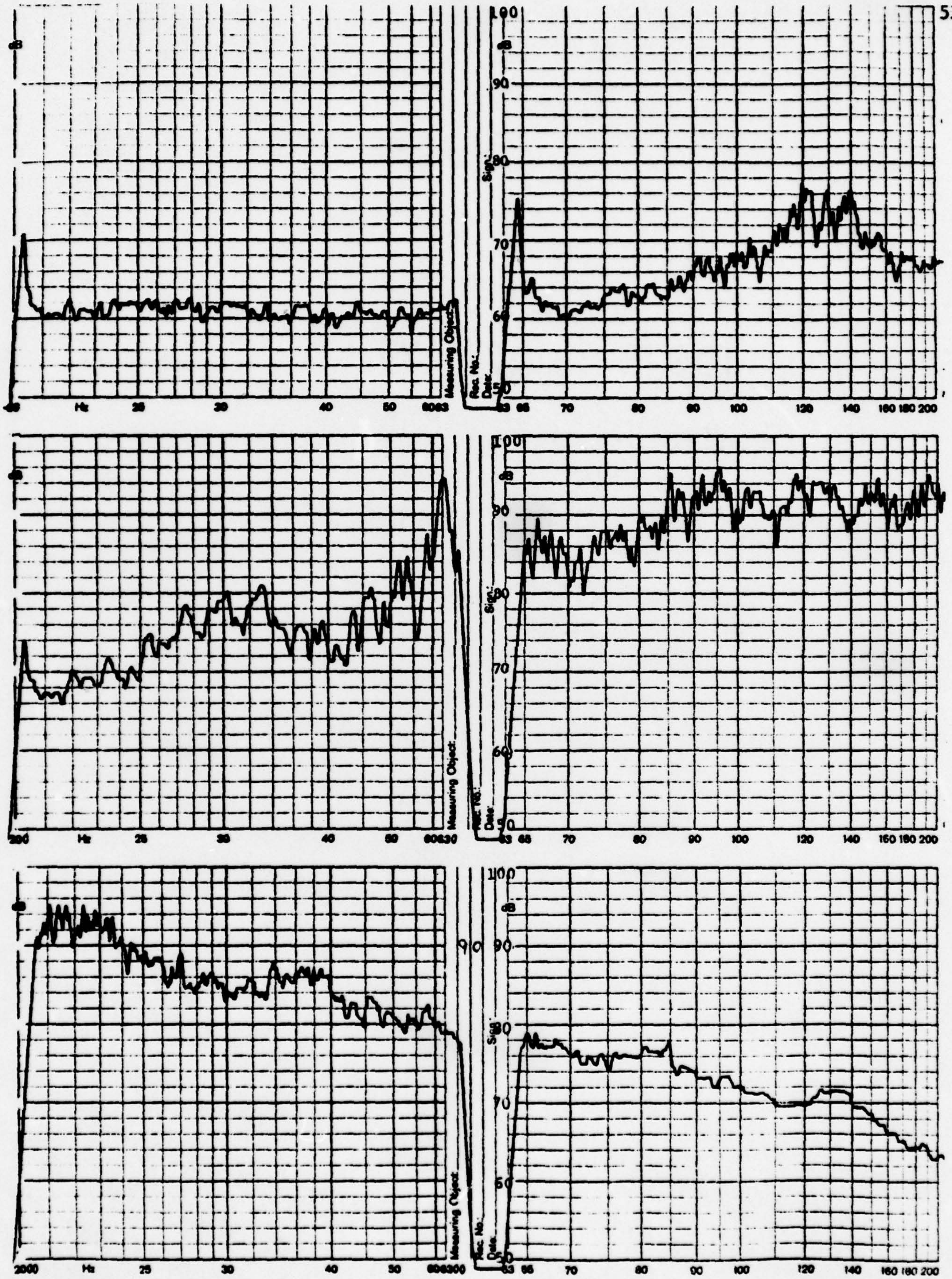


FIGURE 15. Frequency Spectrum of Vibrating Electric Horn #2 with Grill Alarm with Single Projector.

FIGURE 16. Frequency Spectrum of Vibrating Electric Horn #2 Grill Alarm with Double Projector.

FIGURE 17. Frequency Spectrum of Bell Alarm.

FIGURE 18. Frequency Spectrum of Smoke Alarm.

FIGURE 19. Frequency Spectrum of Rotating Diffuser From Microphone Position 1.

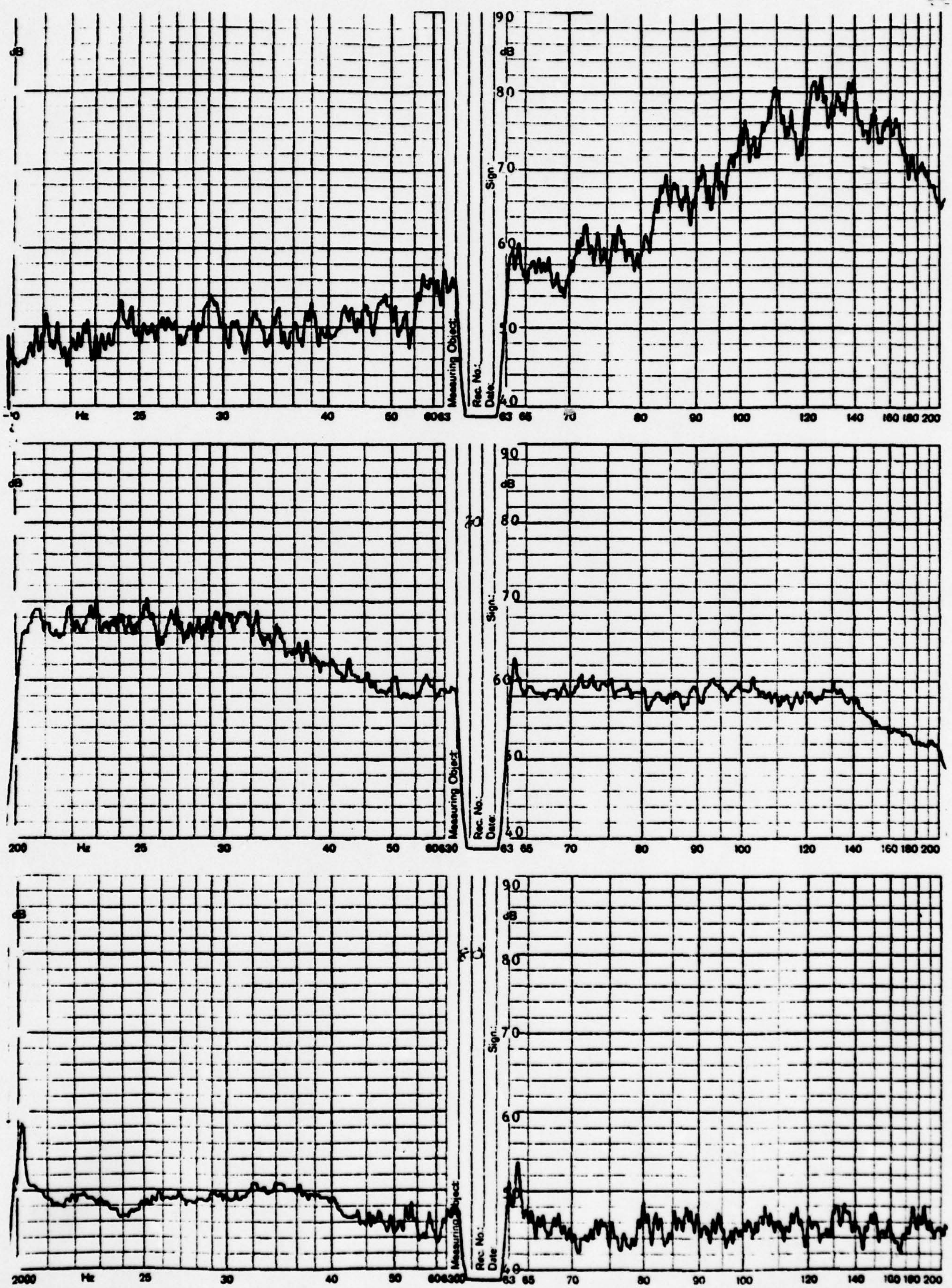
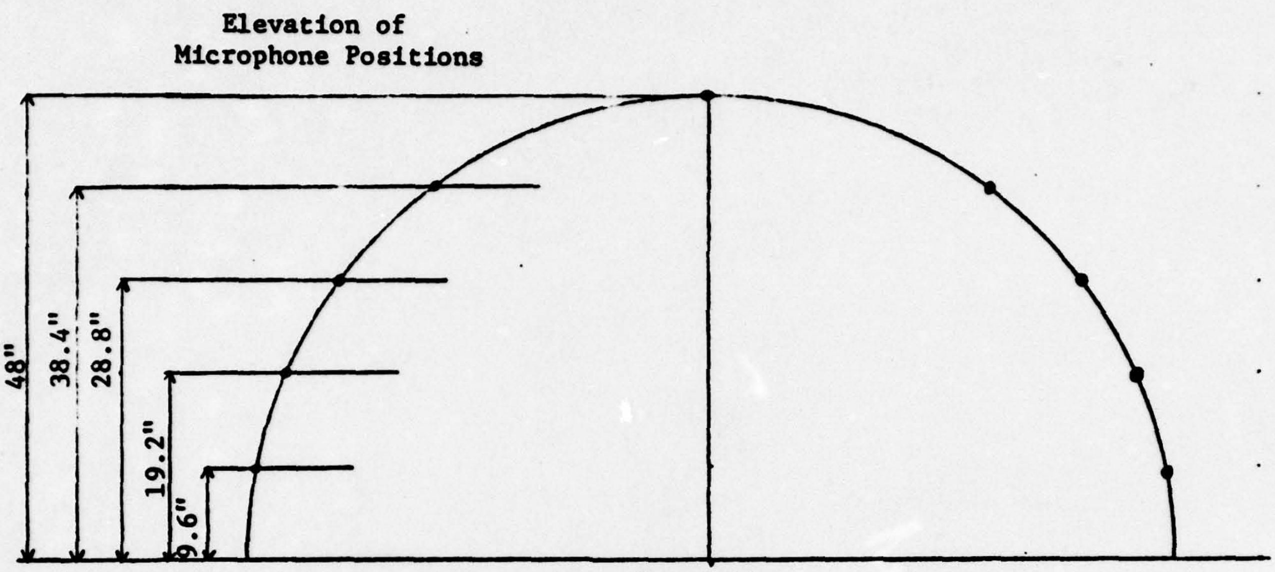
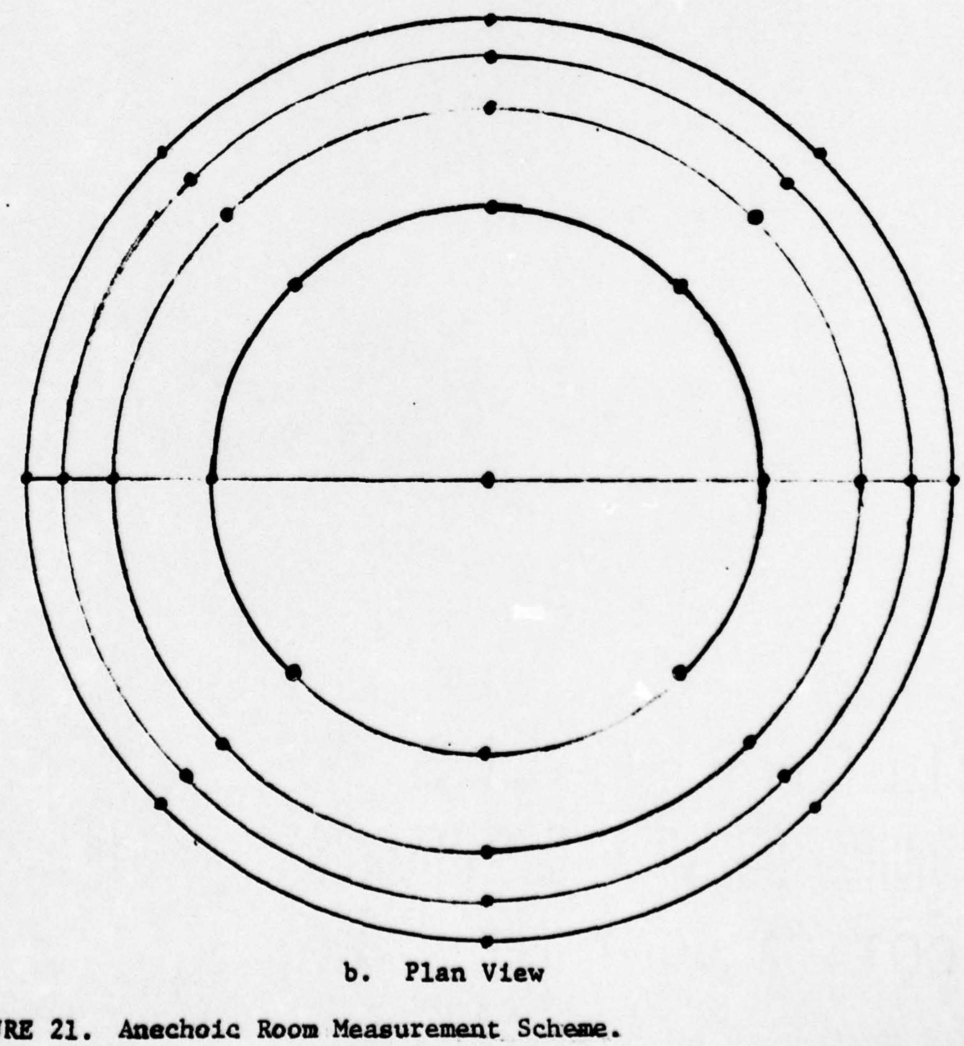


FIGURE 20. Frequency Spectrum of Rotating Diffuser from Microphone Position 2.



a. Front View



b. Plan View

FIGURE 21. Anechoic Room Measurement Scheme.

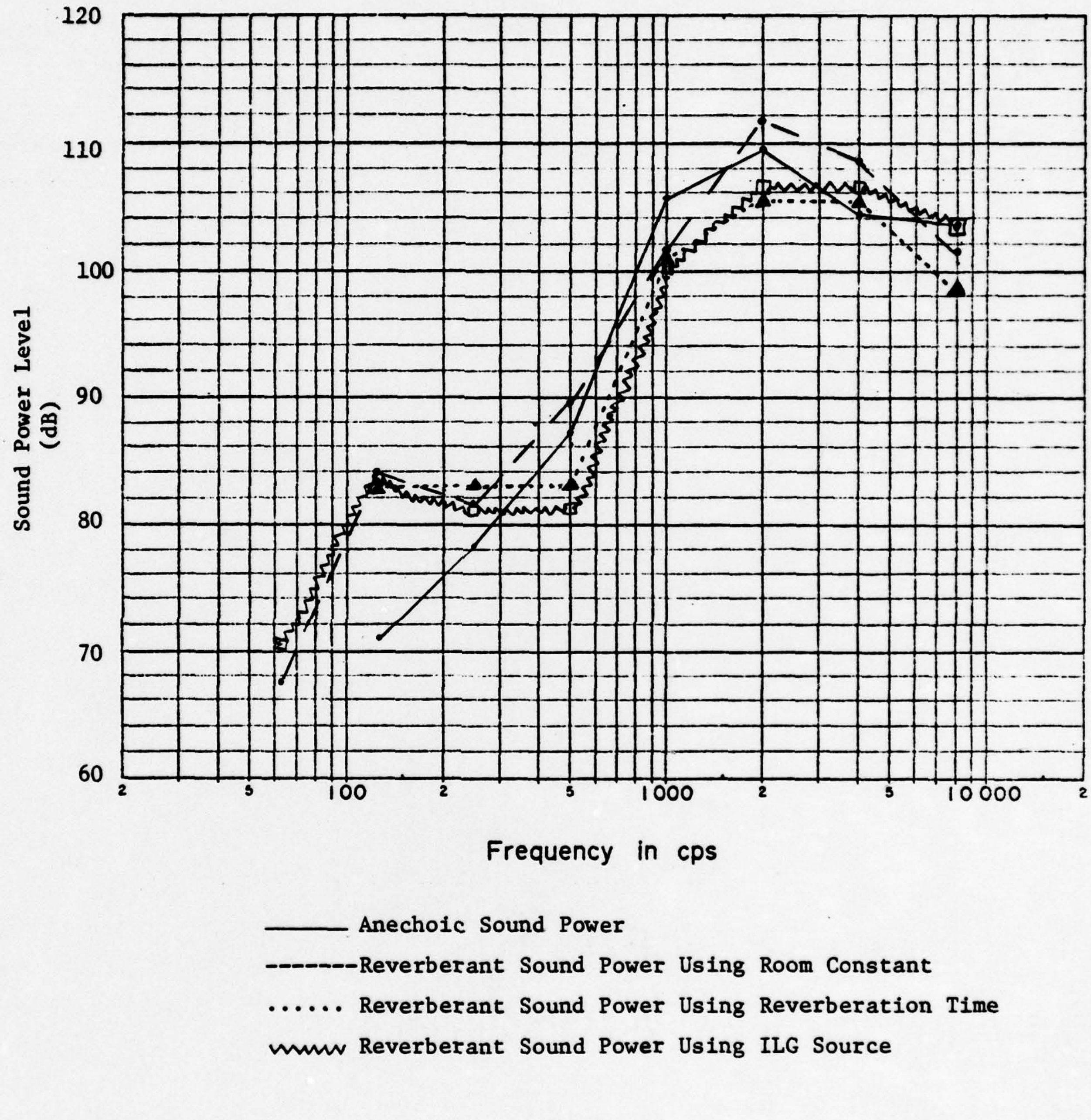
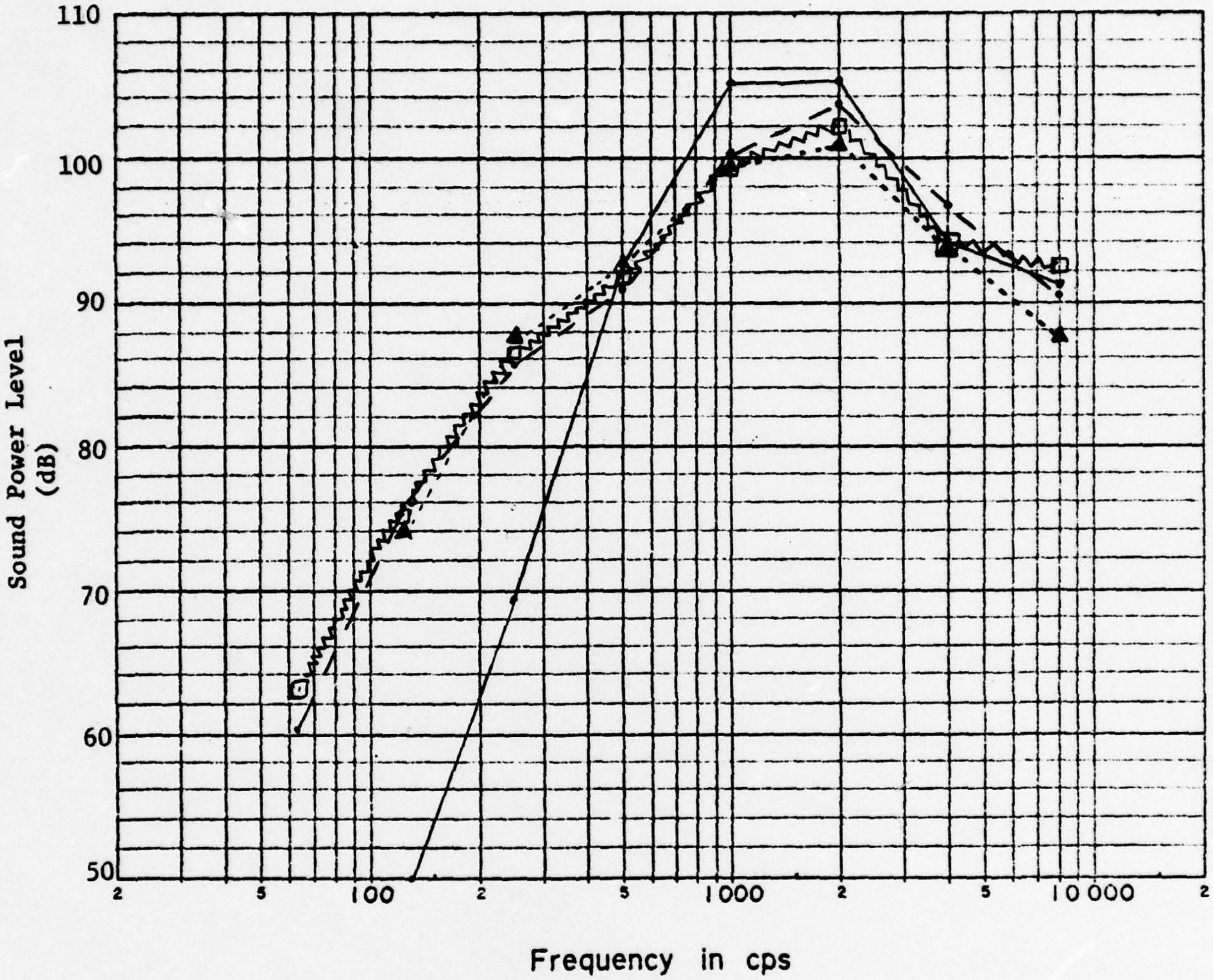


FIGURE 22. Sound Power Comparison for Vibrating Electric Horn #1 Grill Alarm.



——— Anechoic Sound Power

------ Reverberant Sound Power Using Room Constant

...... Reverberant Sound Power Using Reverberation Time

wwww Reverberant Sound Power Using ILG Source

FIGURE 23. Sound Power Comparison for Vibrating Electric Horn #2 Grill Alarm.

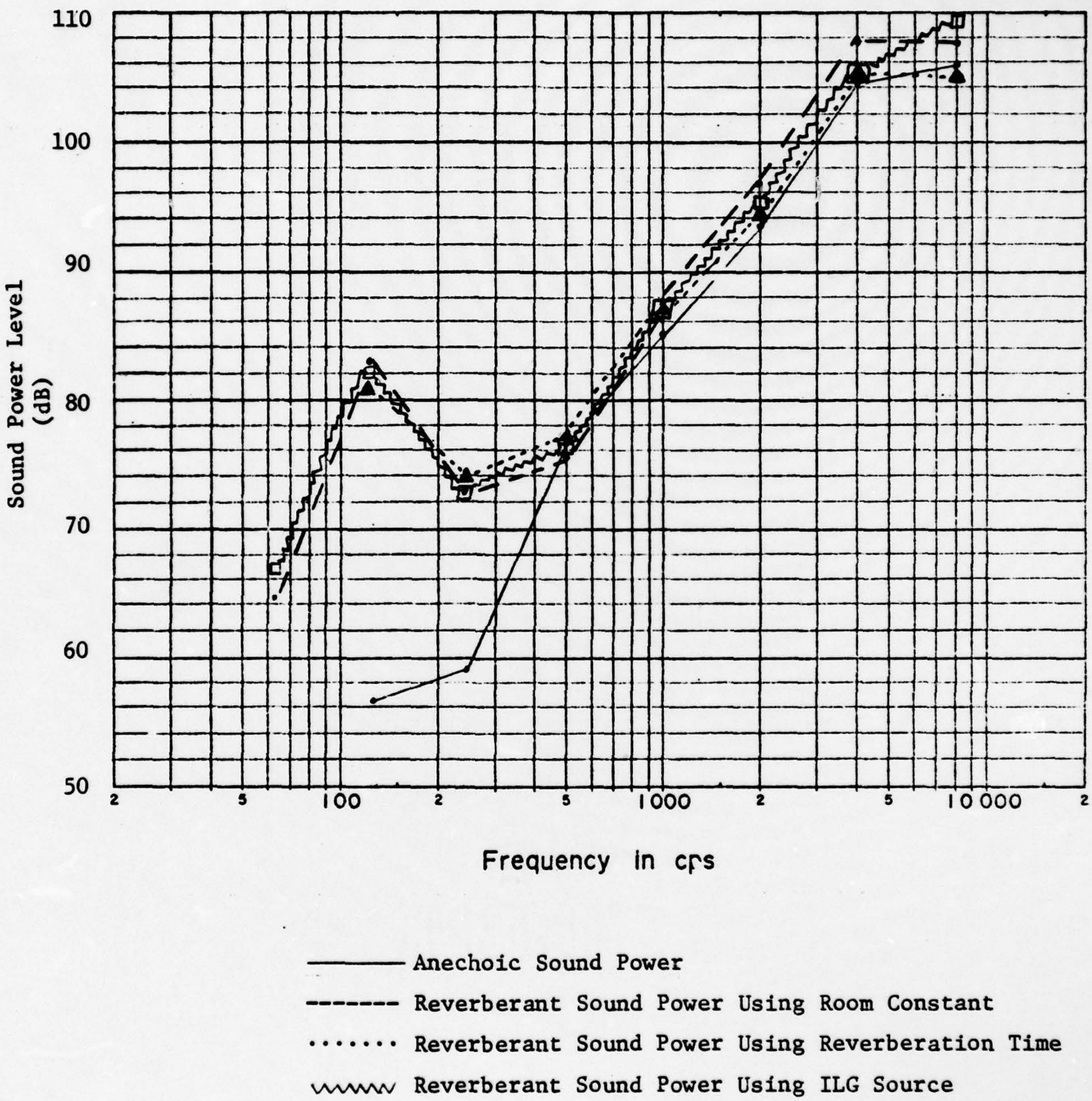


FIGURE 24. Sound Power Comparison for Bell Alarm.

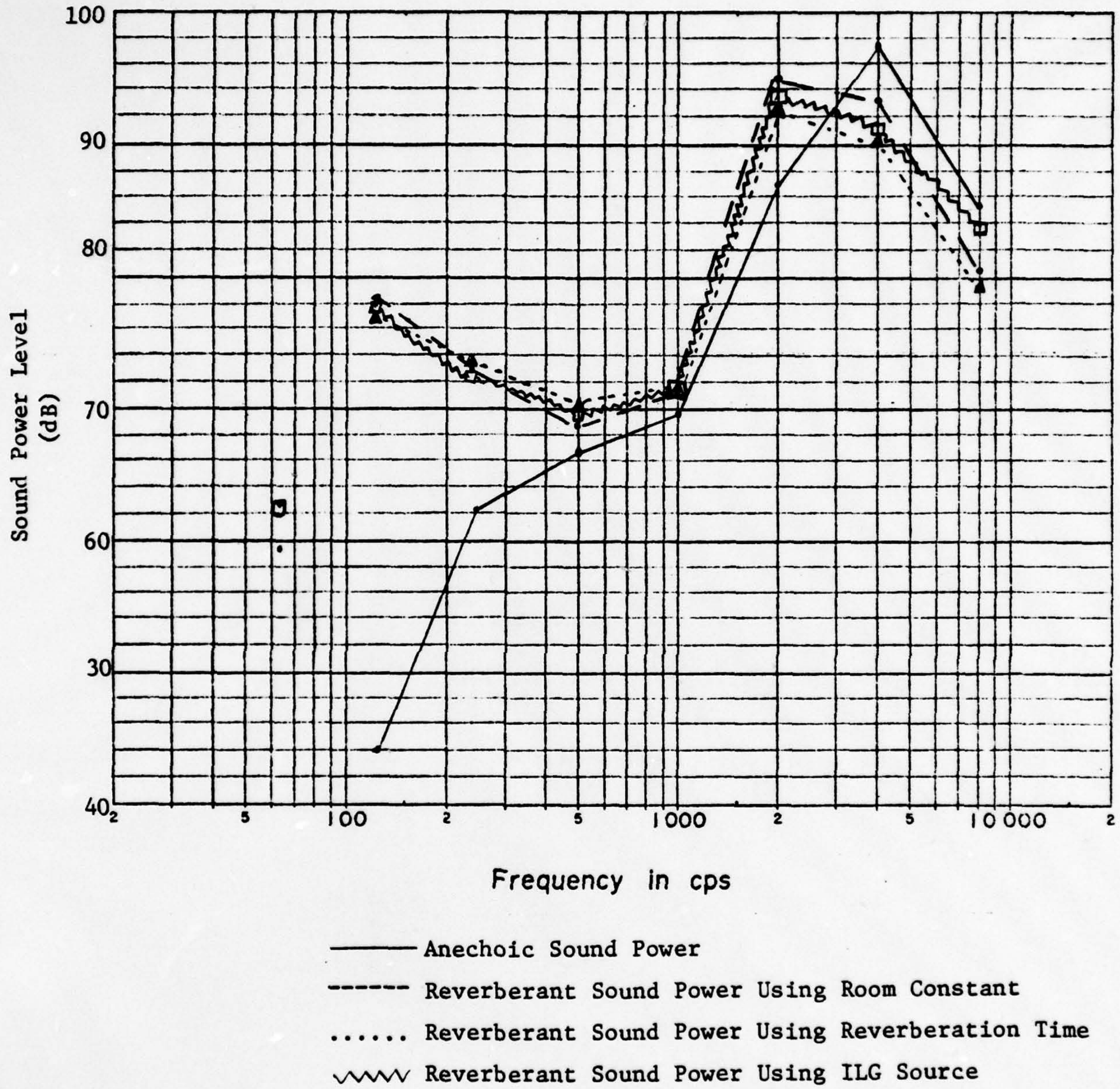
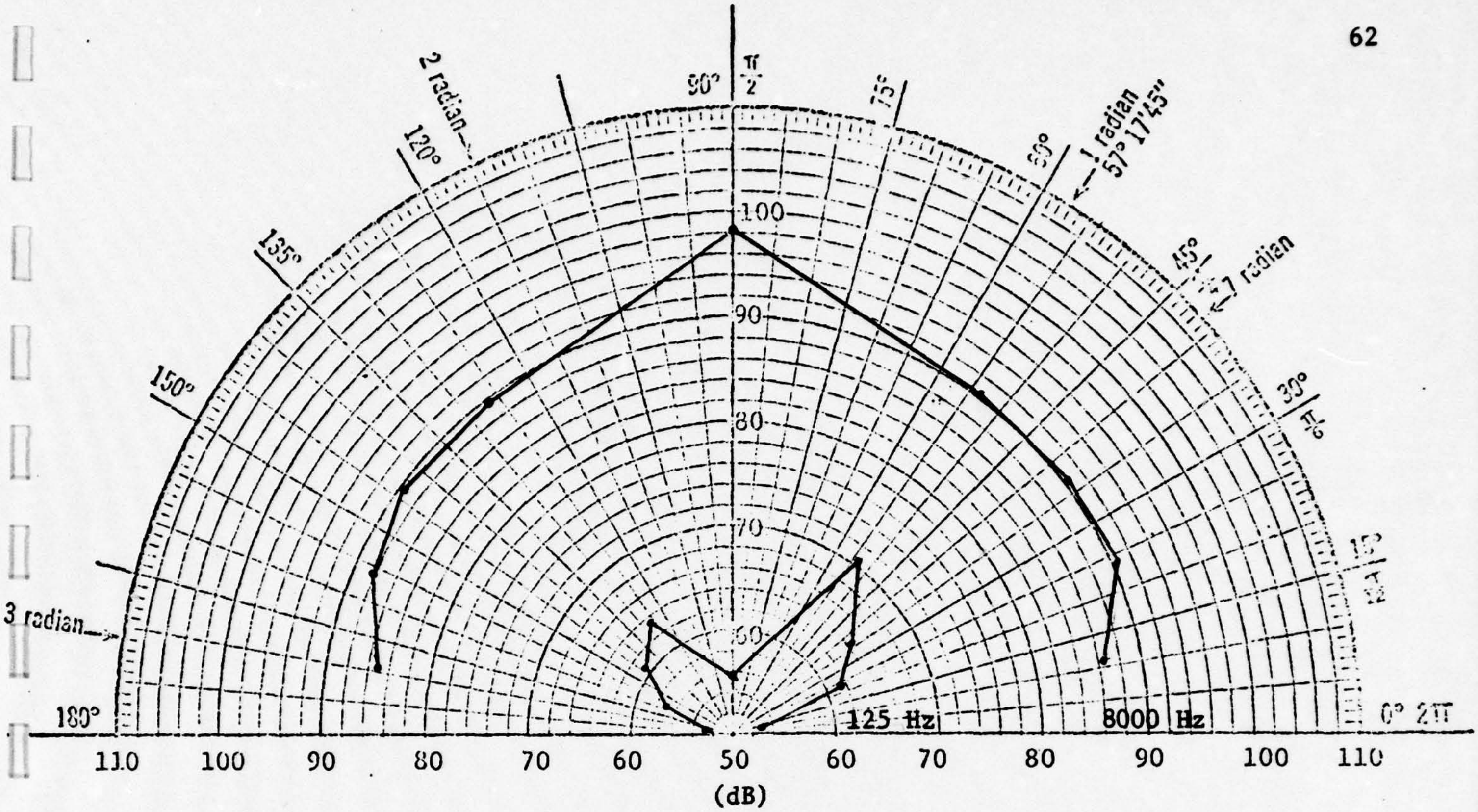


FIGURE 25. Sound Power for Smoke Alarm.



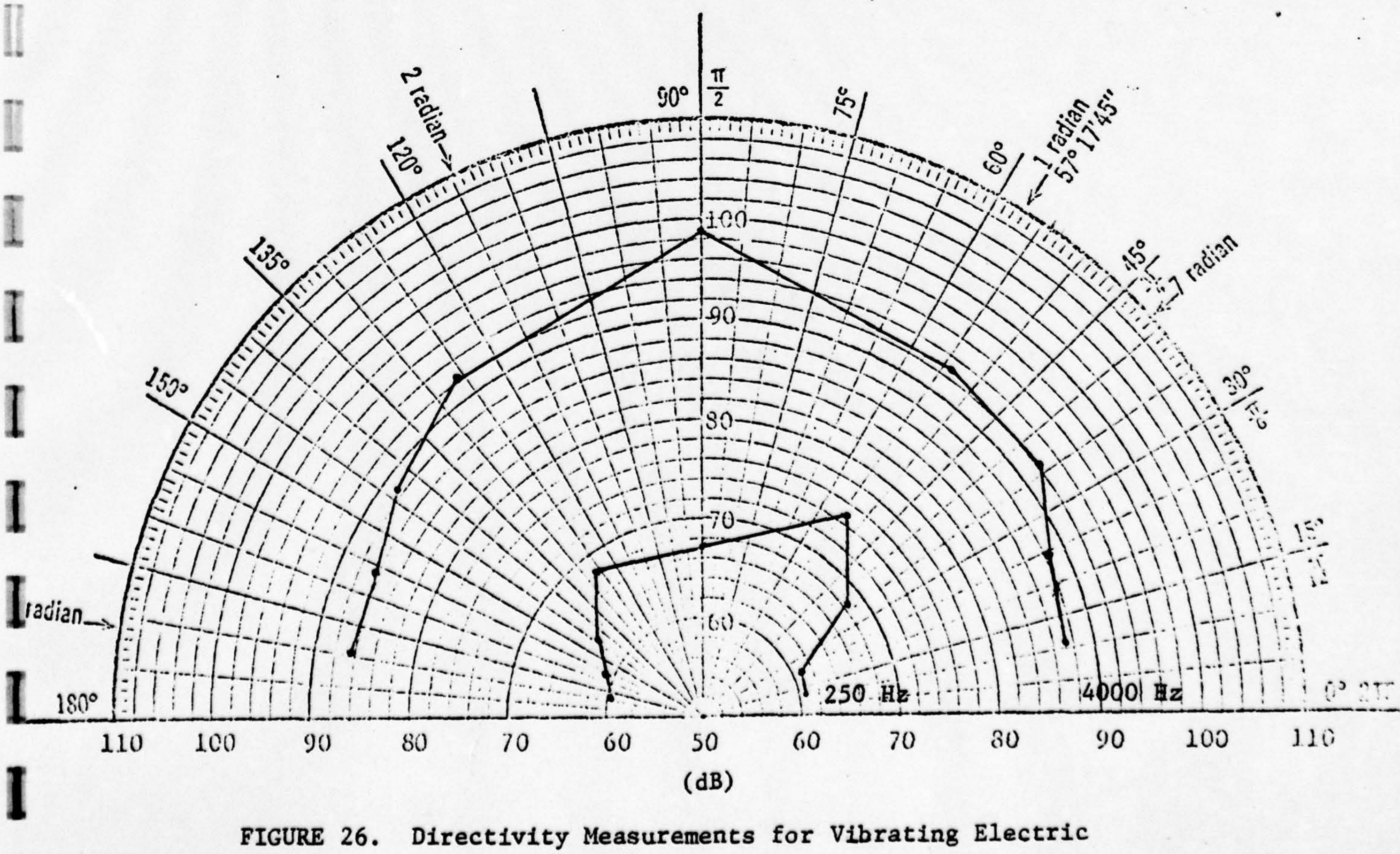
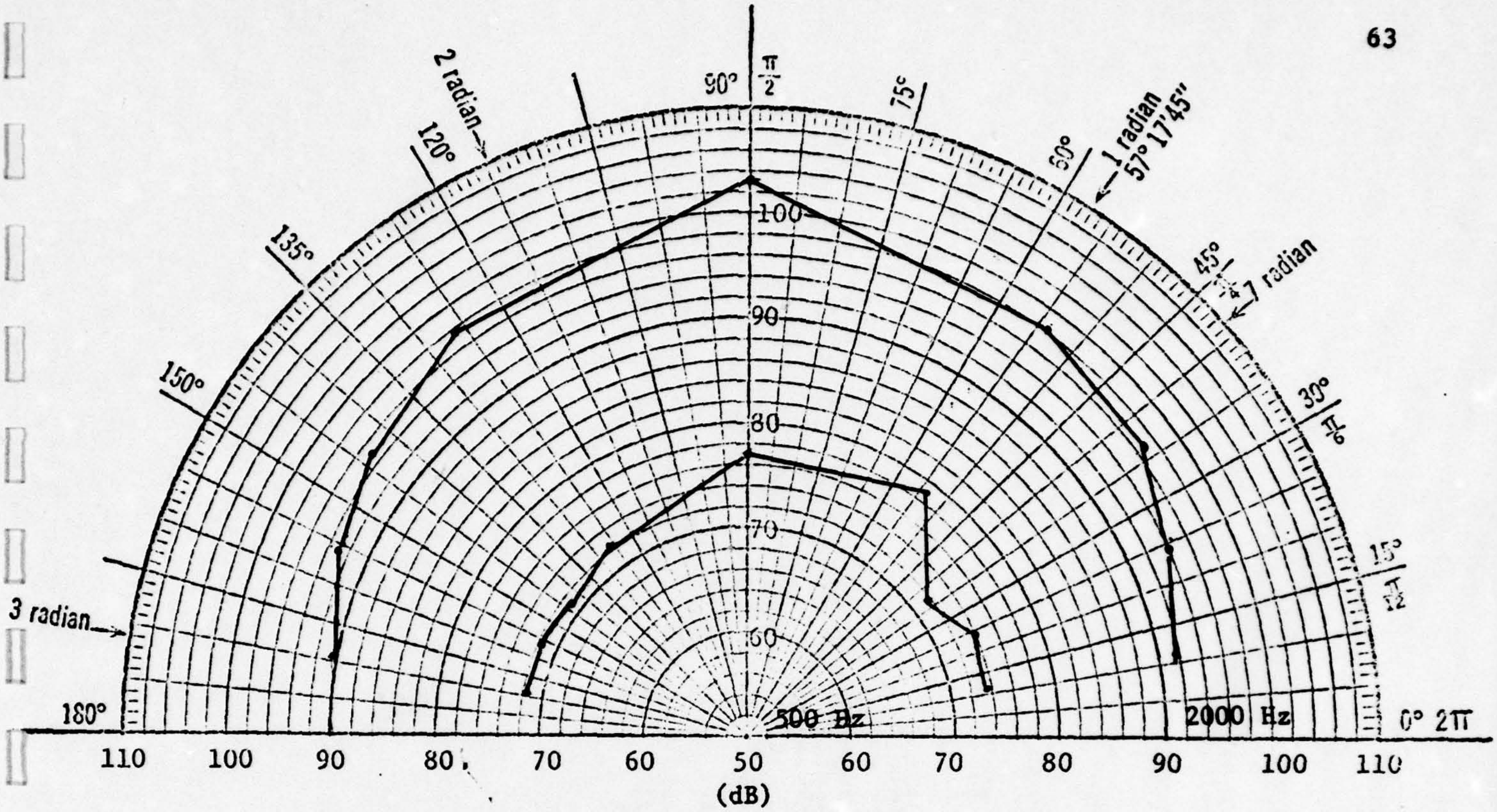


FIGURE 26. Directivity Measurements for Vibrating Electric Horn #1 Grill Alarm.



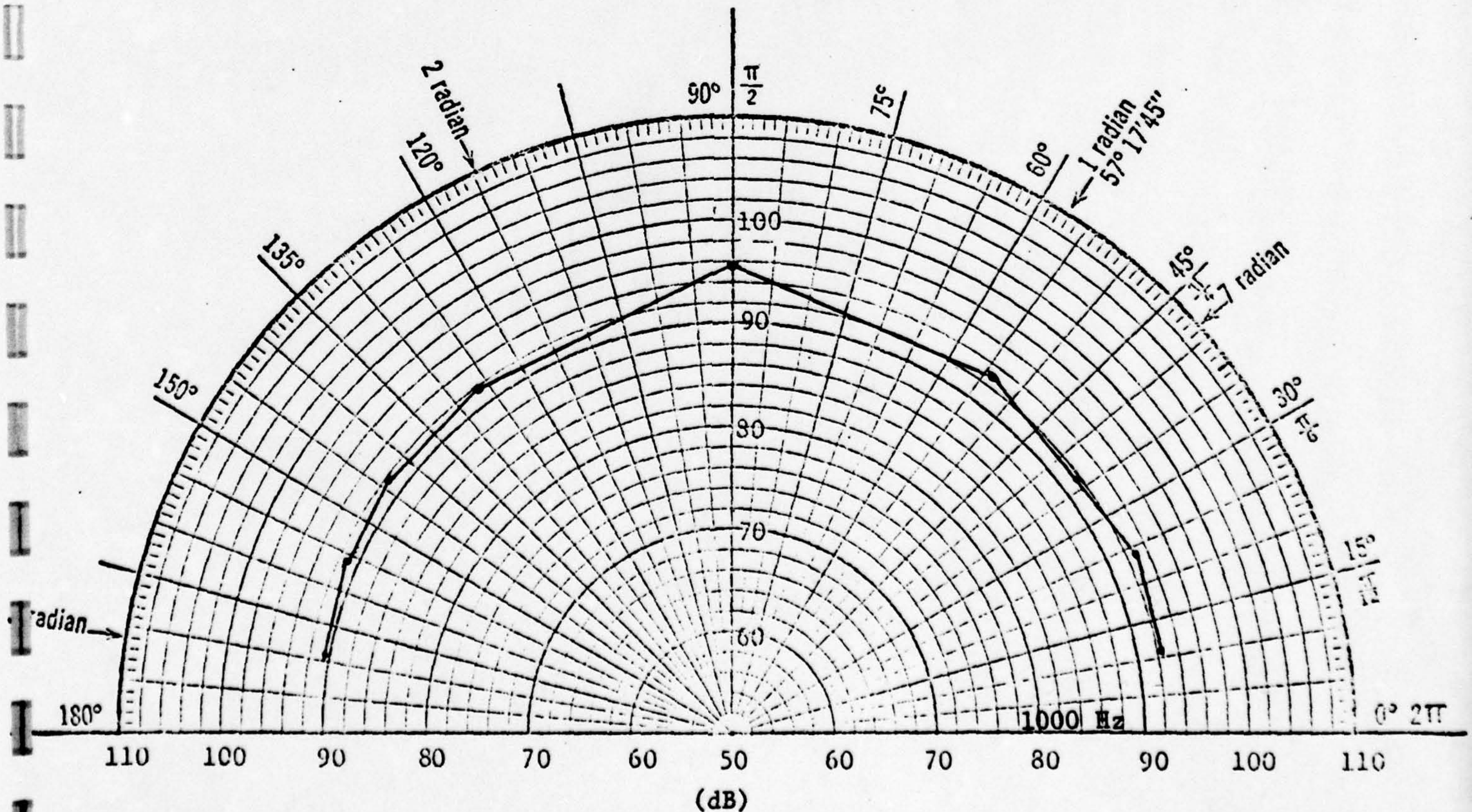
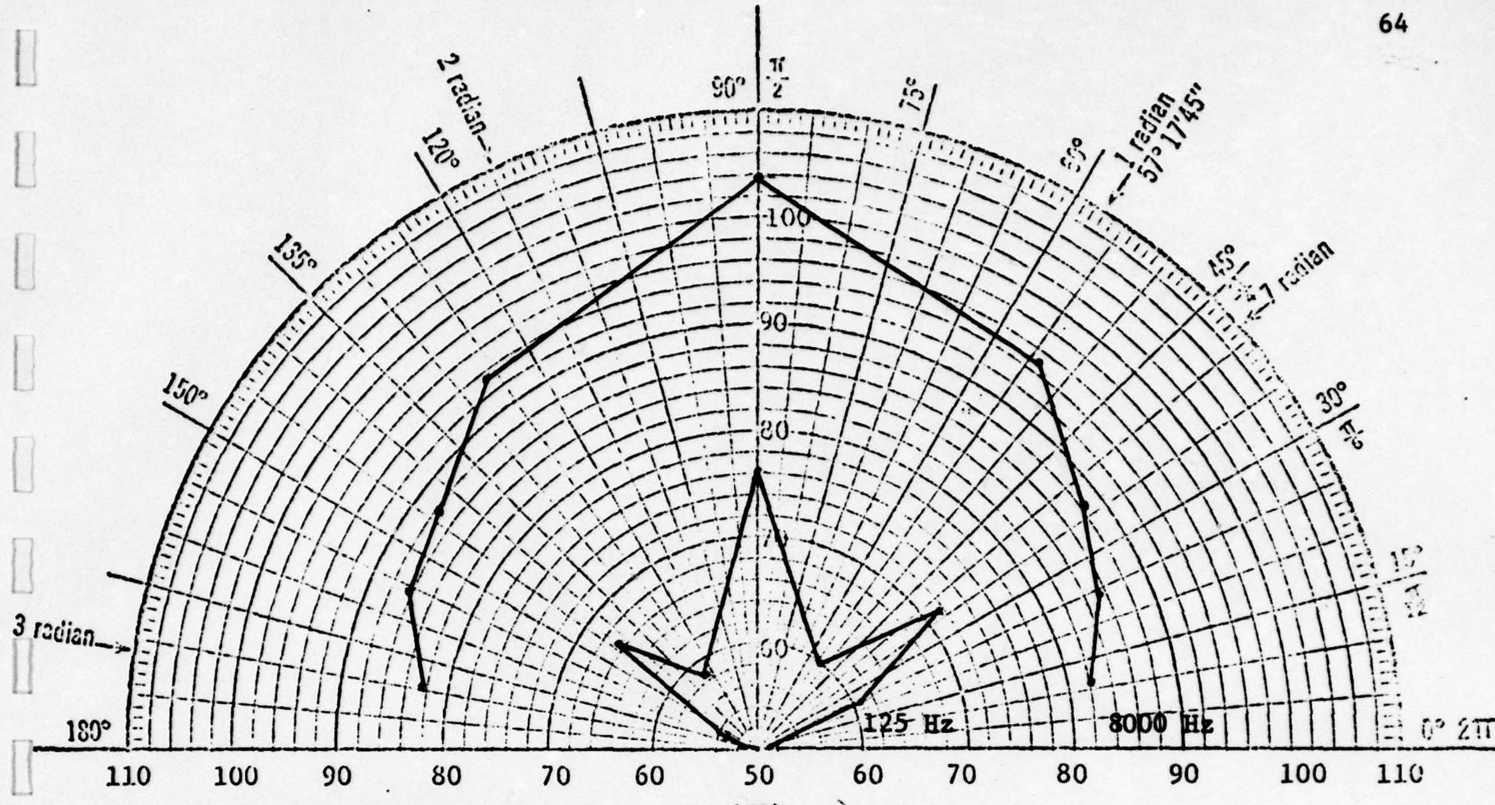


FIGURE 27. Directivity Measurements for Vibrating Electric Horn #1 Grill Alarm.



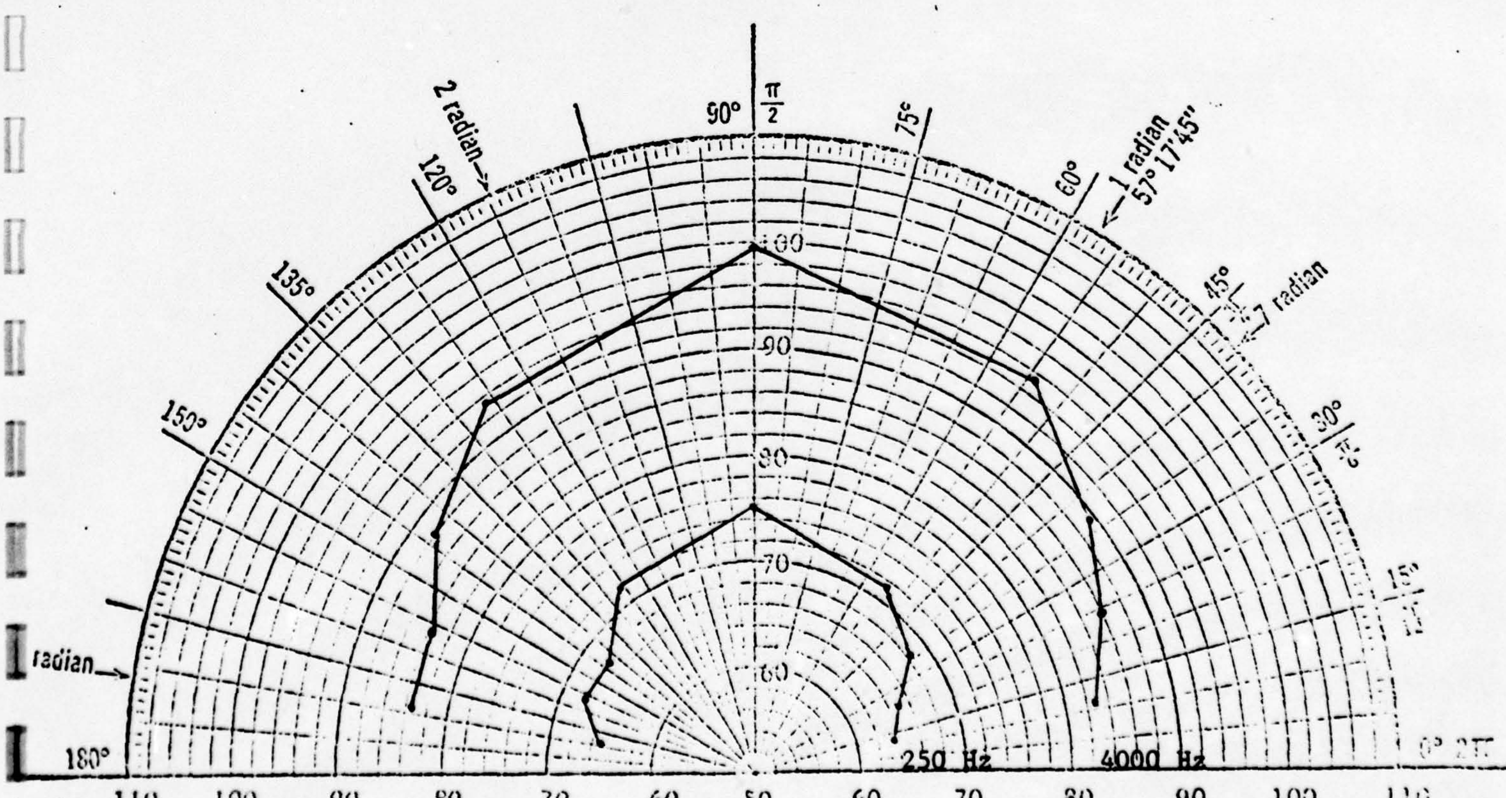
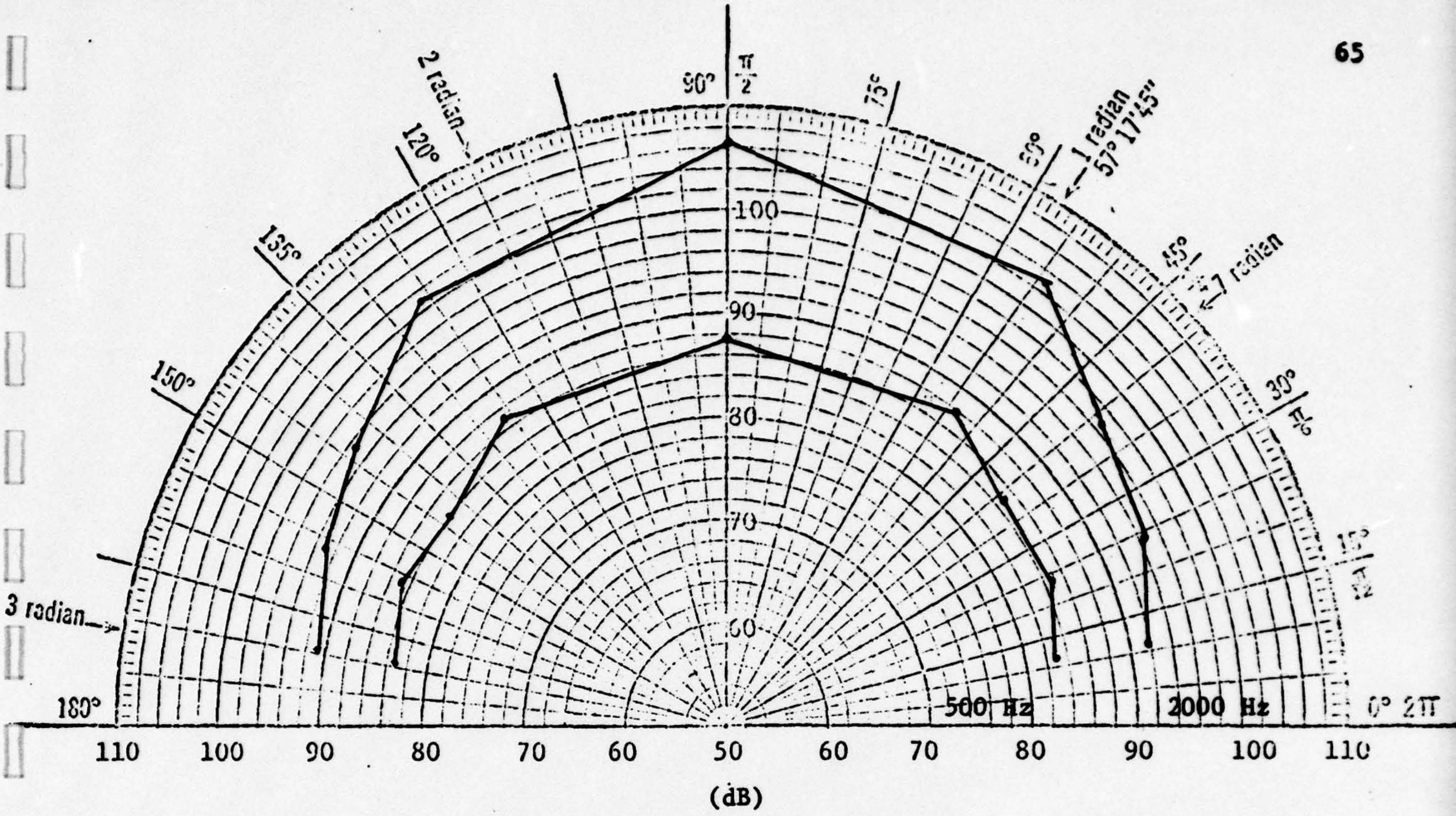


FIGURE 28. Directivity Measurements for Vibrating Electric Horn #1 Grill Alarm with Projector.



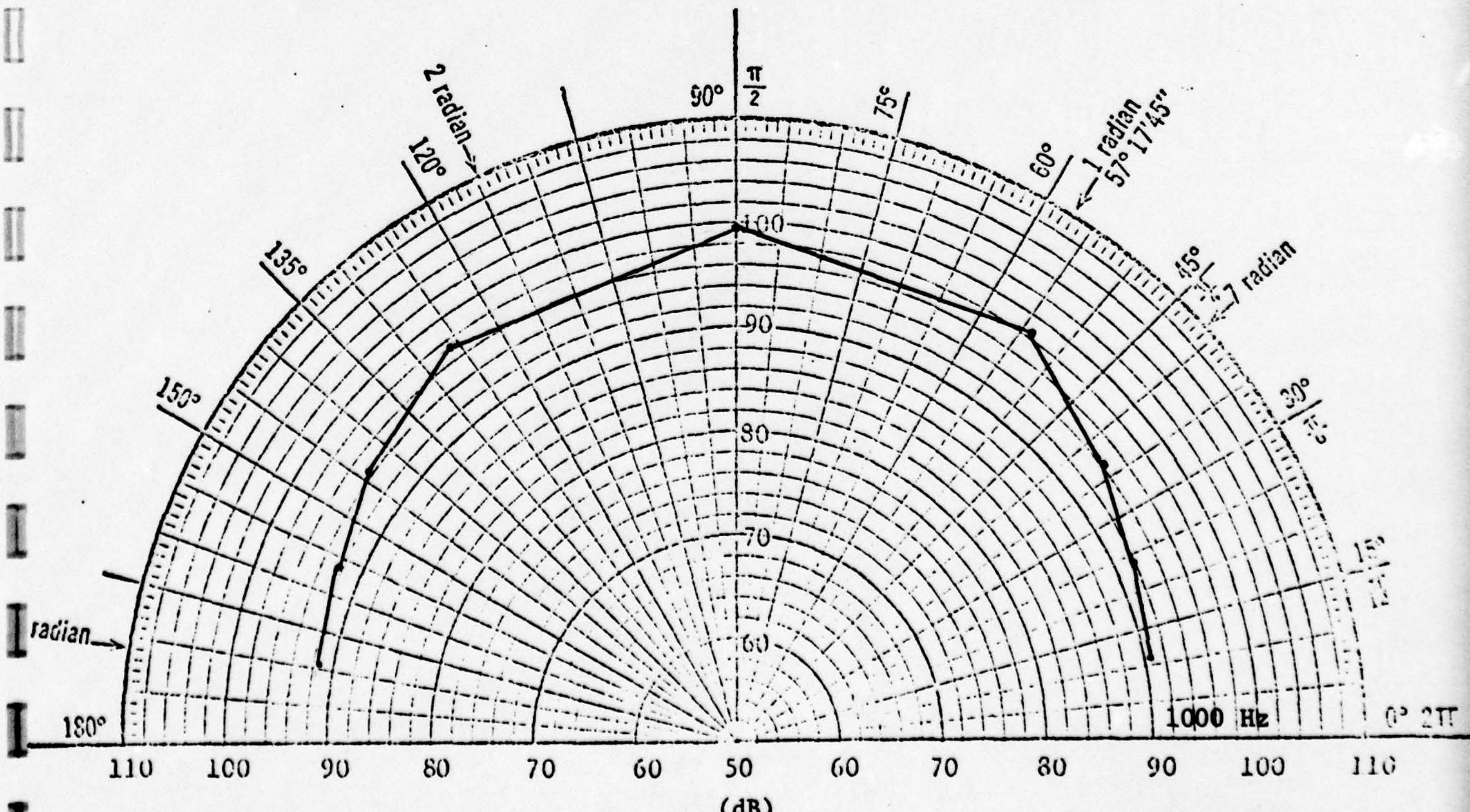
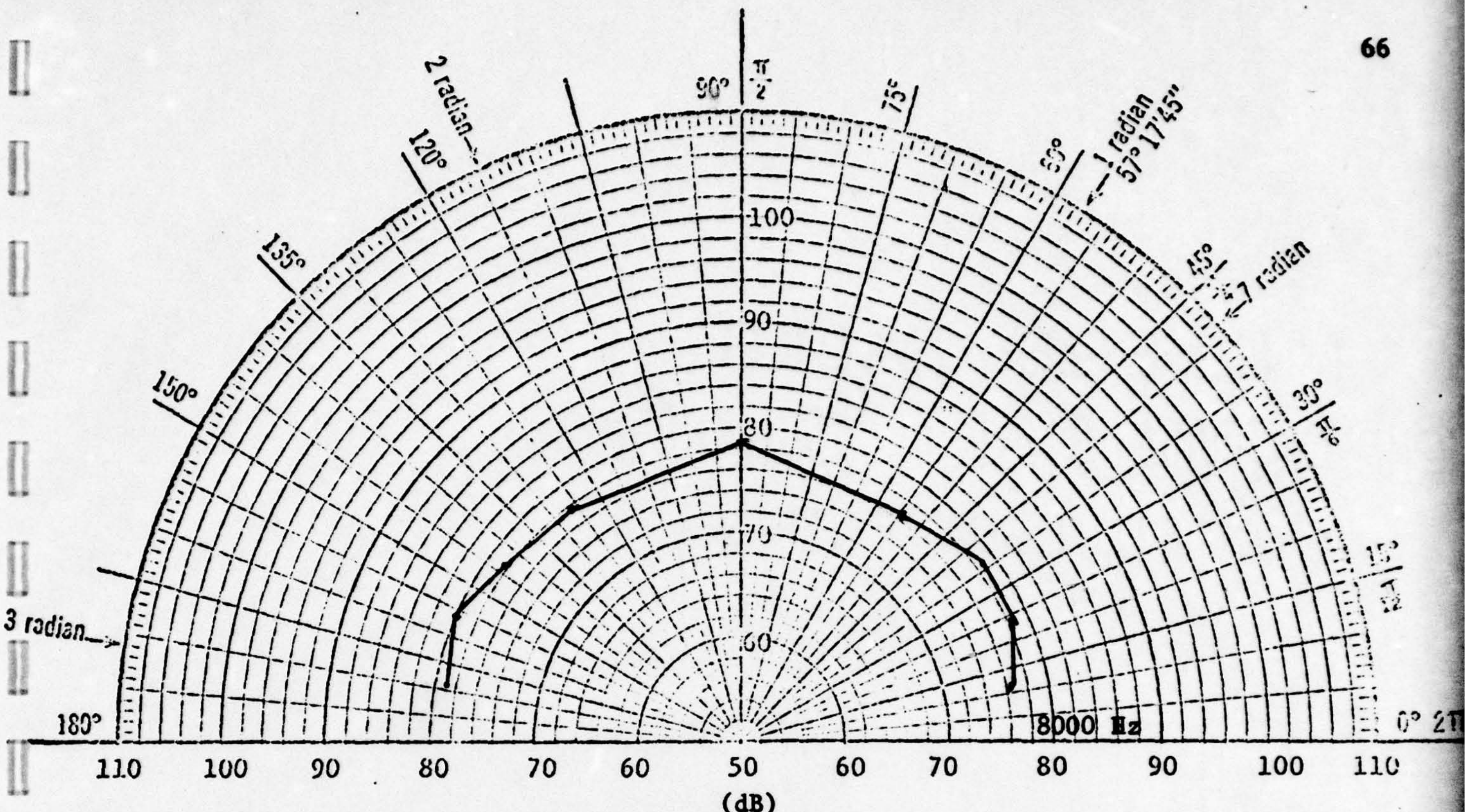


FIGURE 29. Directivity Measurements for Vibrating Electric Horn #1 Grill Alarm with Projector.



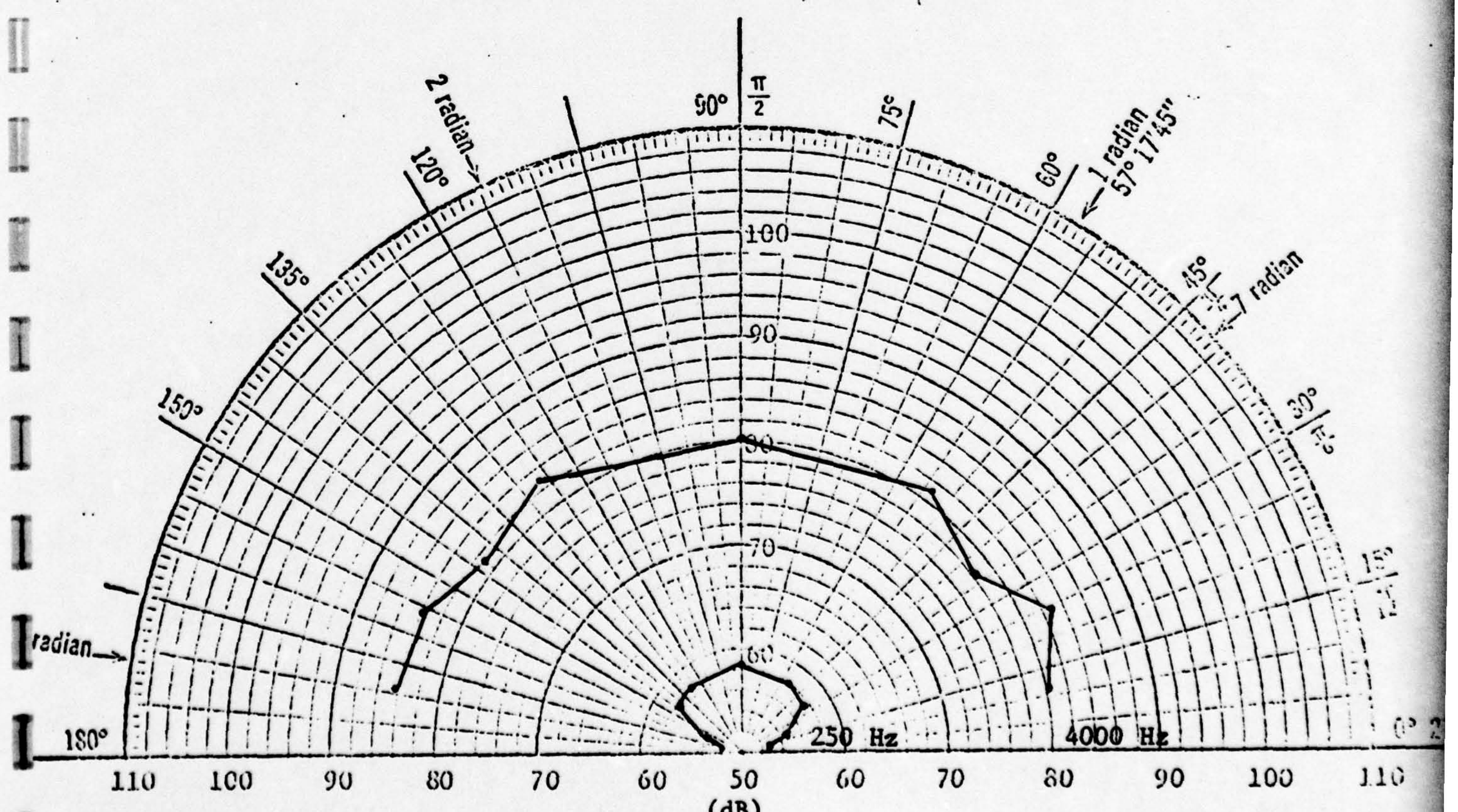


FIGURE 30. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm.

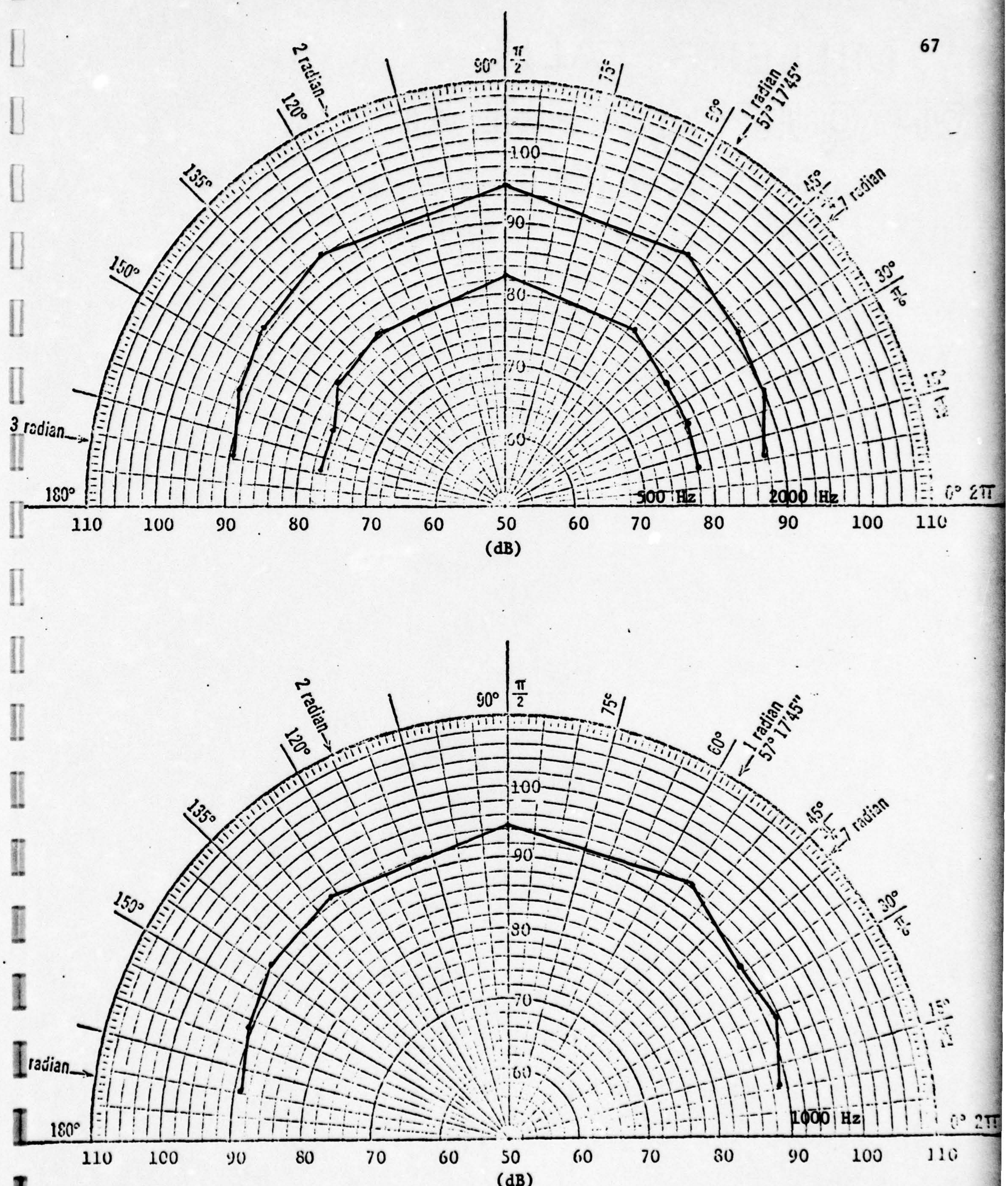
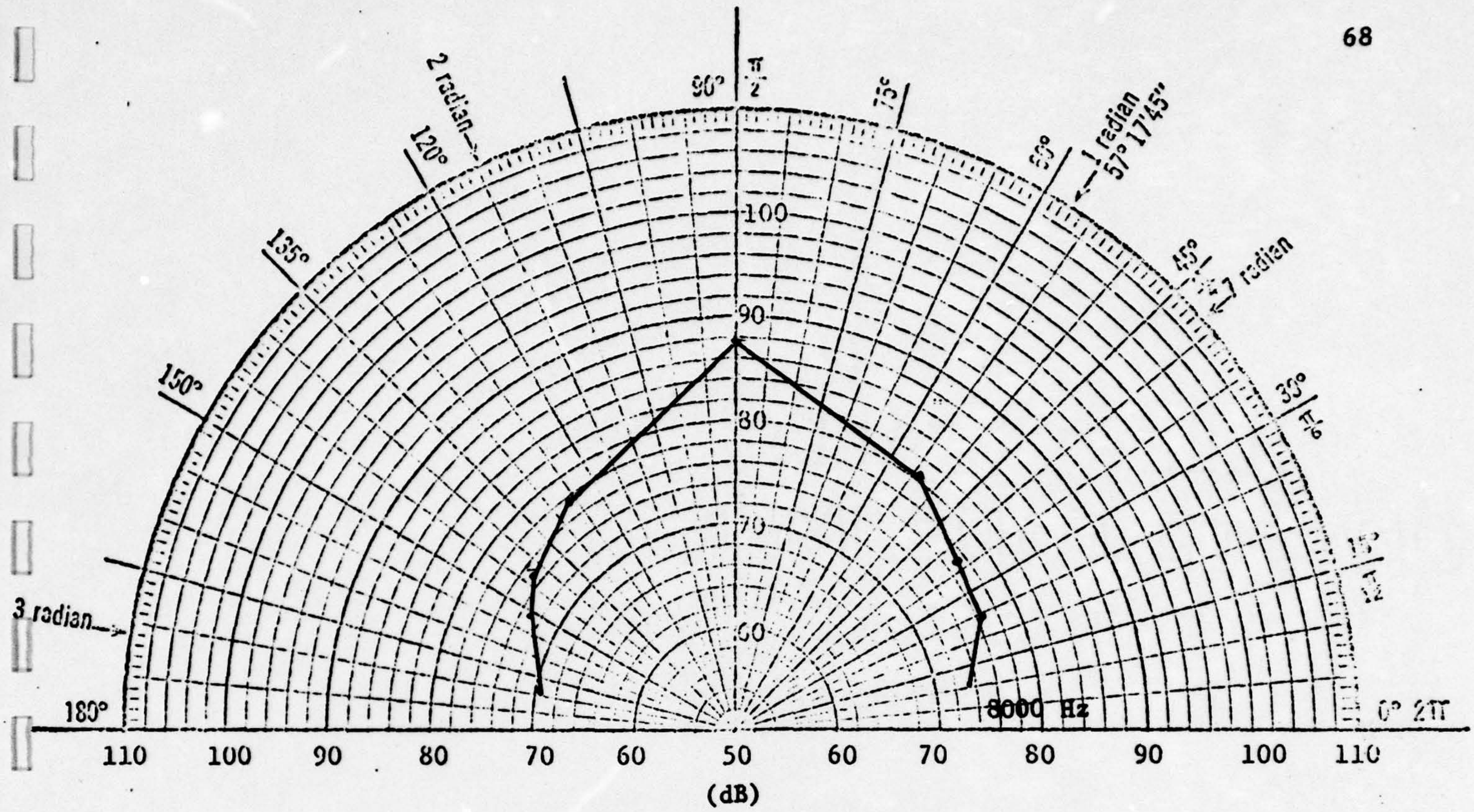


FIGURE 31. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm.



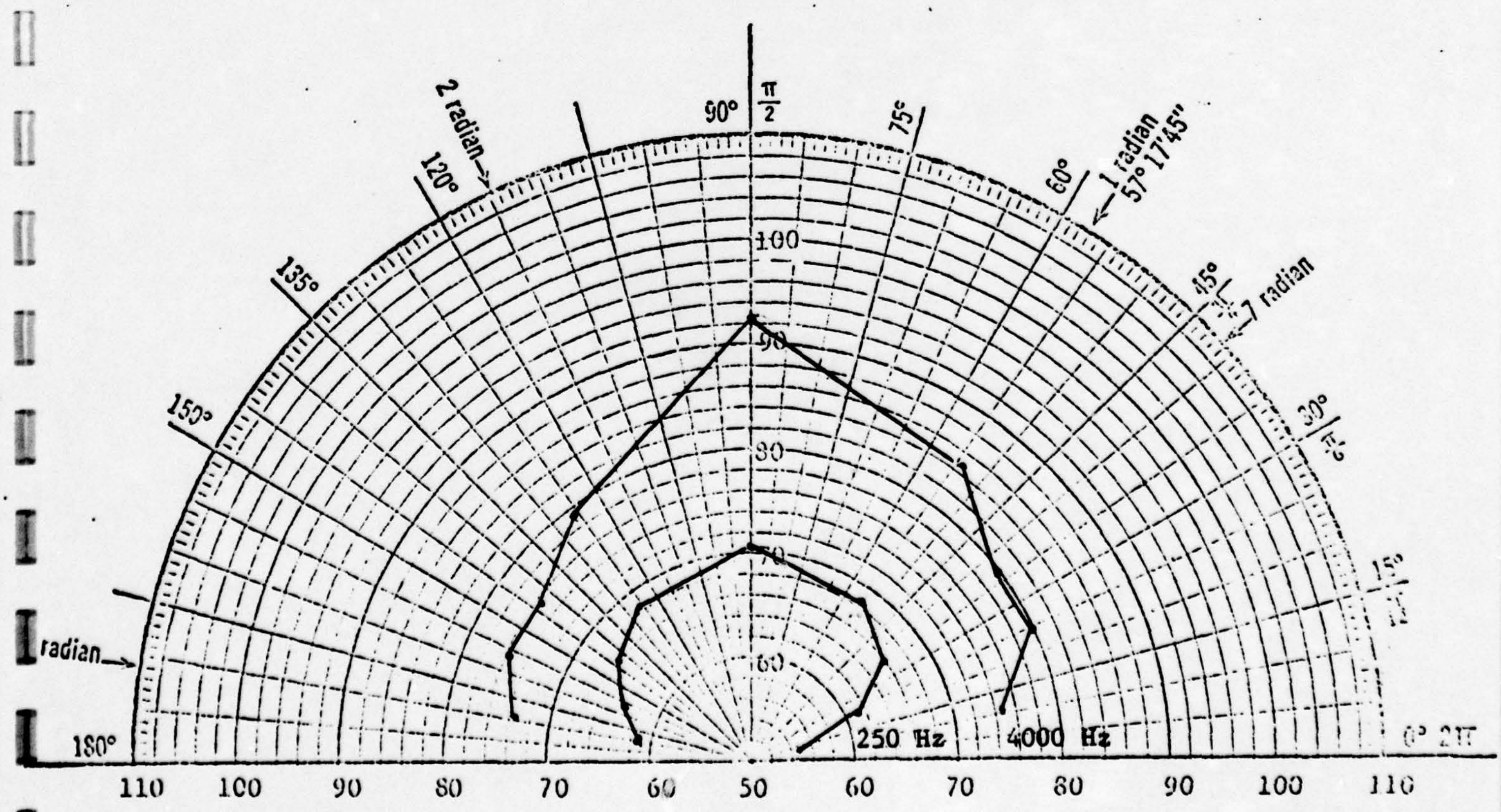


FIGURE 32. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm with Projector.

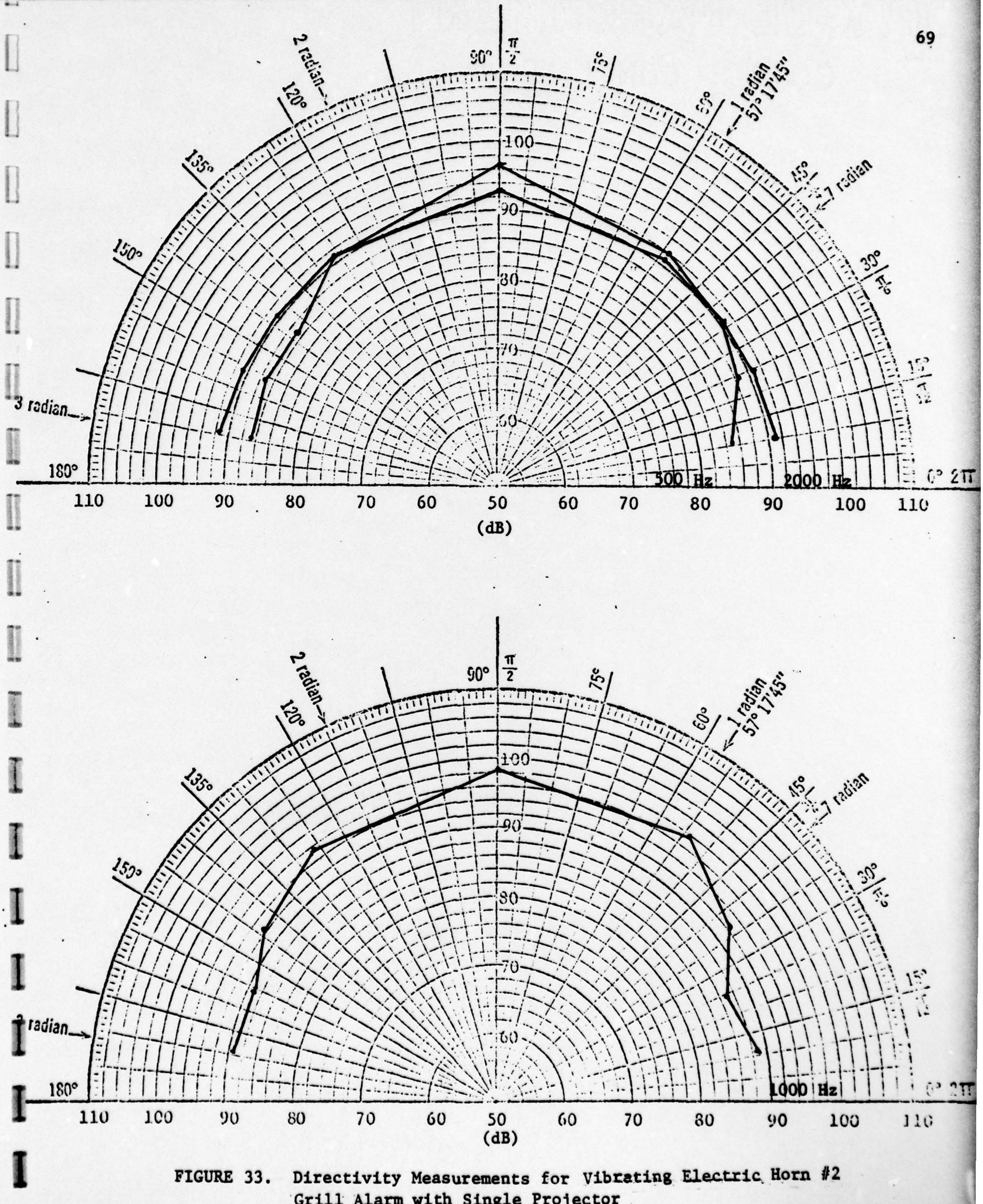
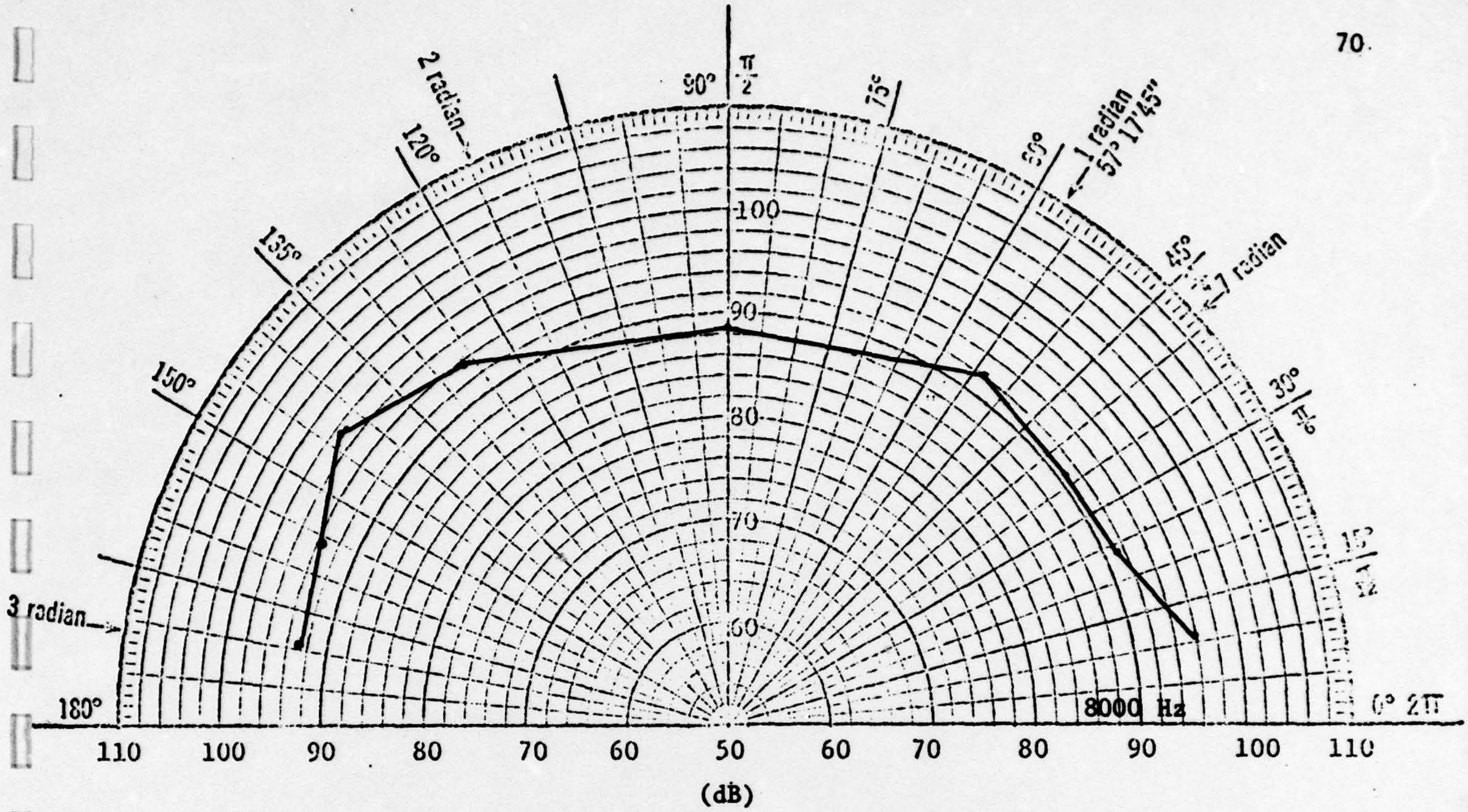


FIGURE 33. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm with Single Projector



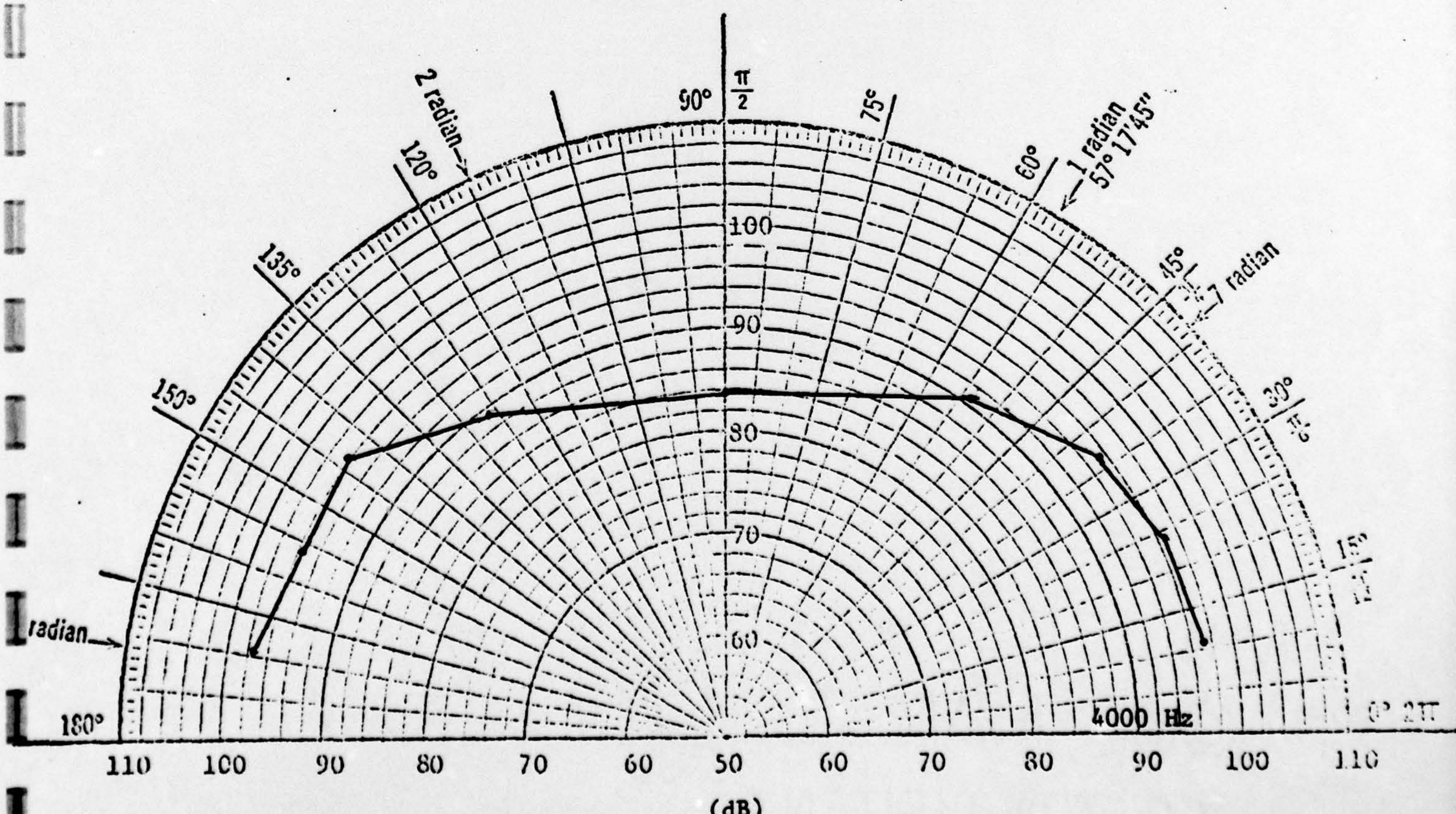
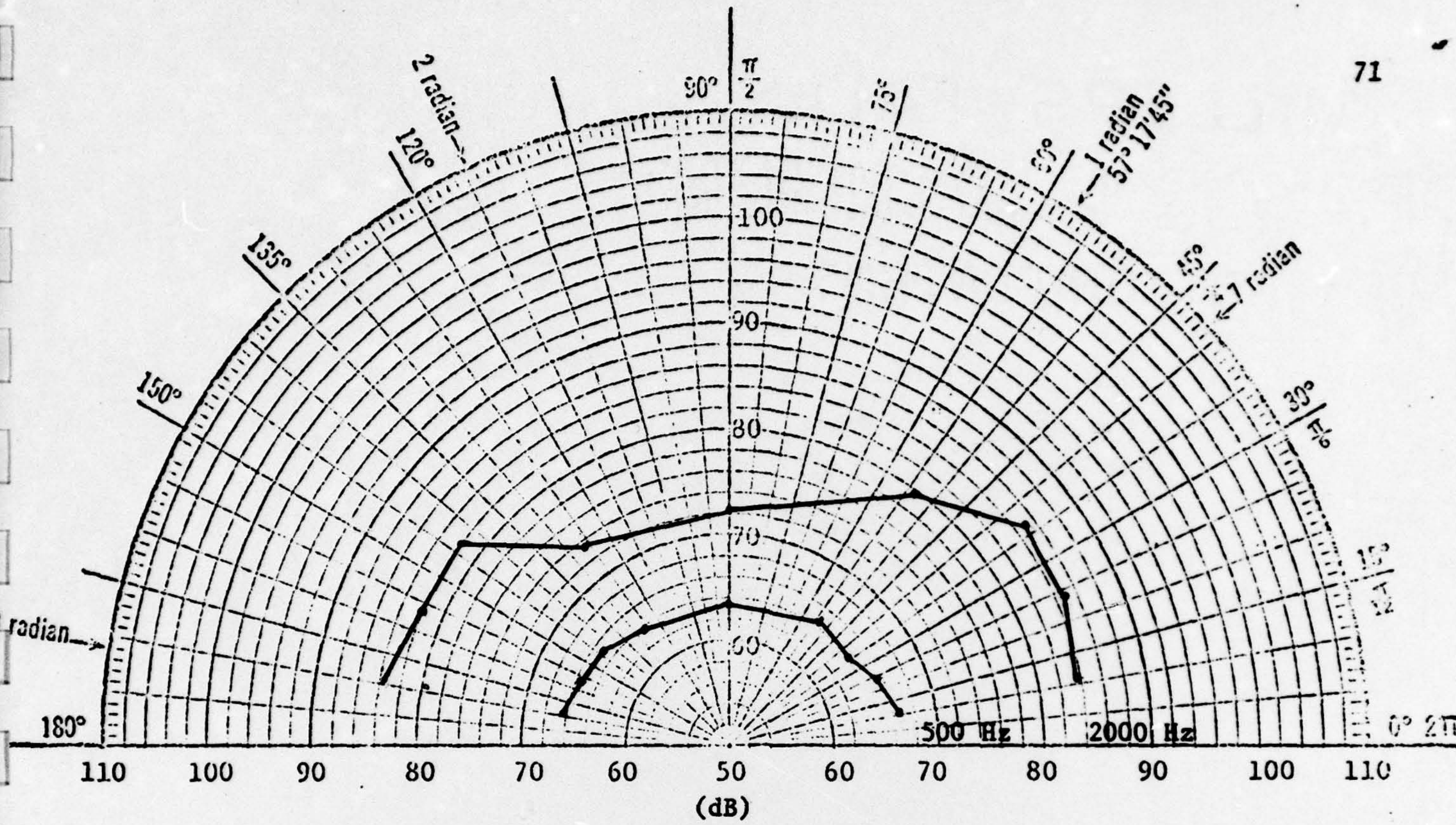


FIGURE 34. Directivity Measurements for Bell Alarm.



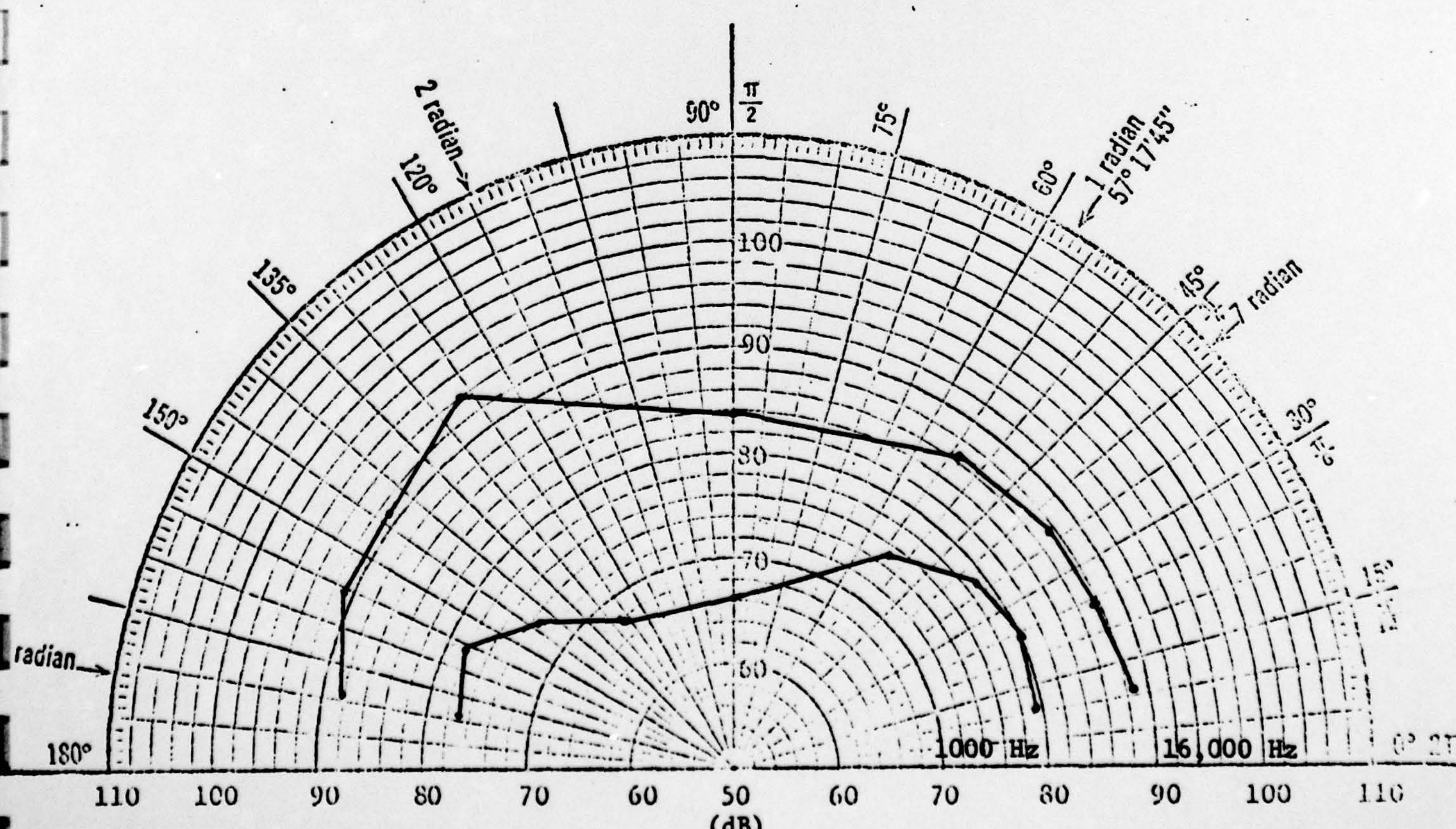


FIGURE 35. Directivity Measurements for Bell Alarm.

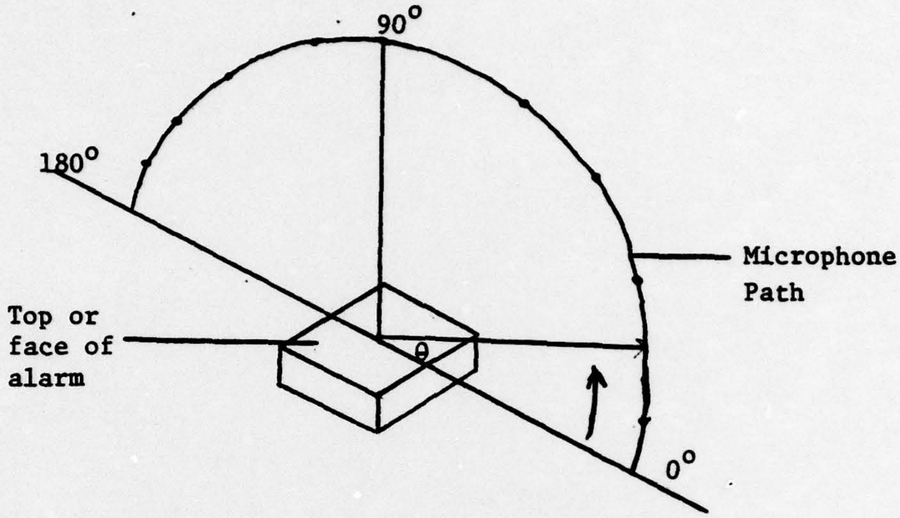


FIGURE 36. Directivity Measurement Scheme.

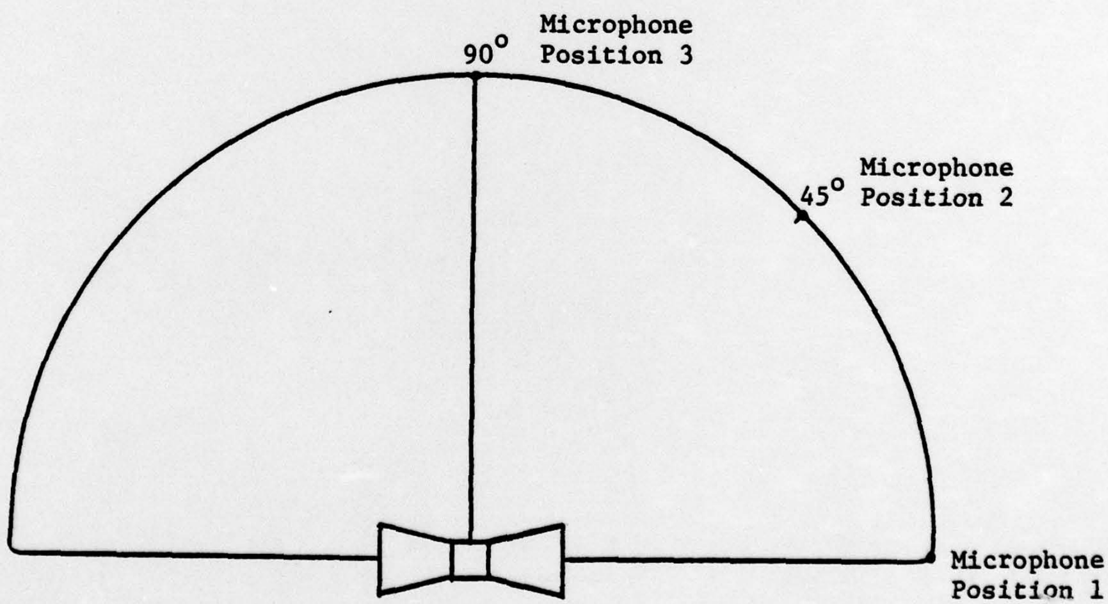
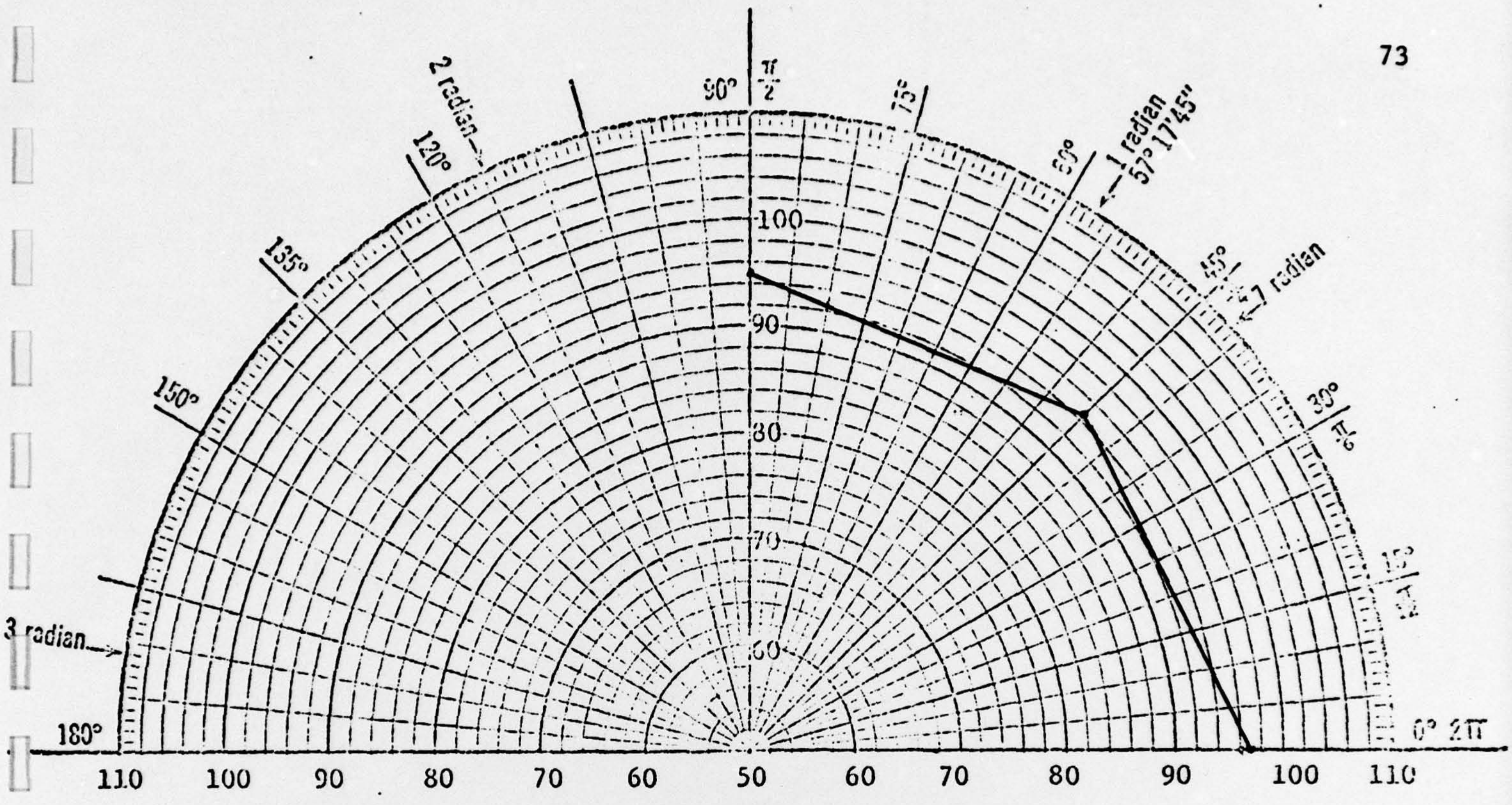
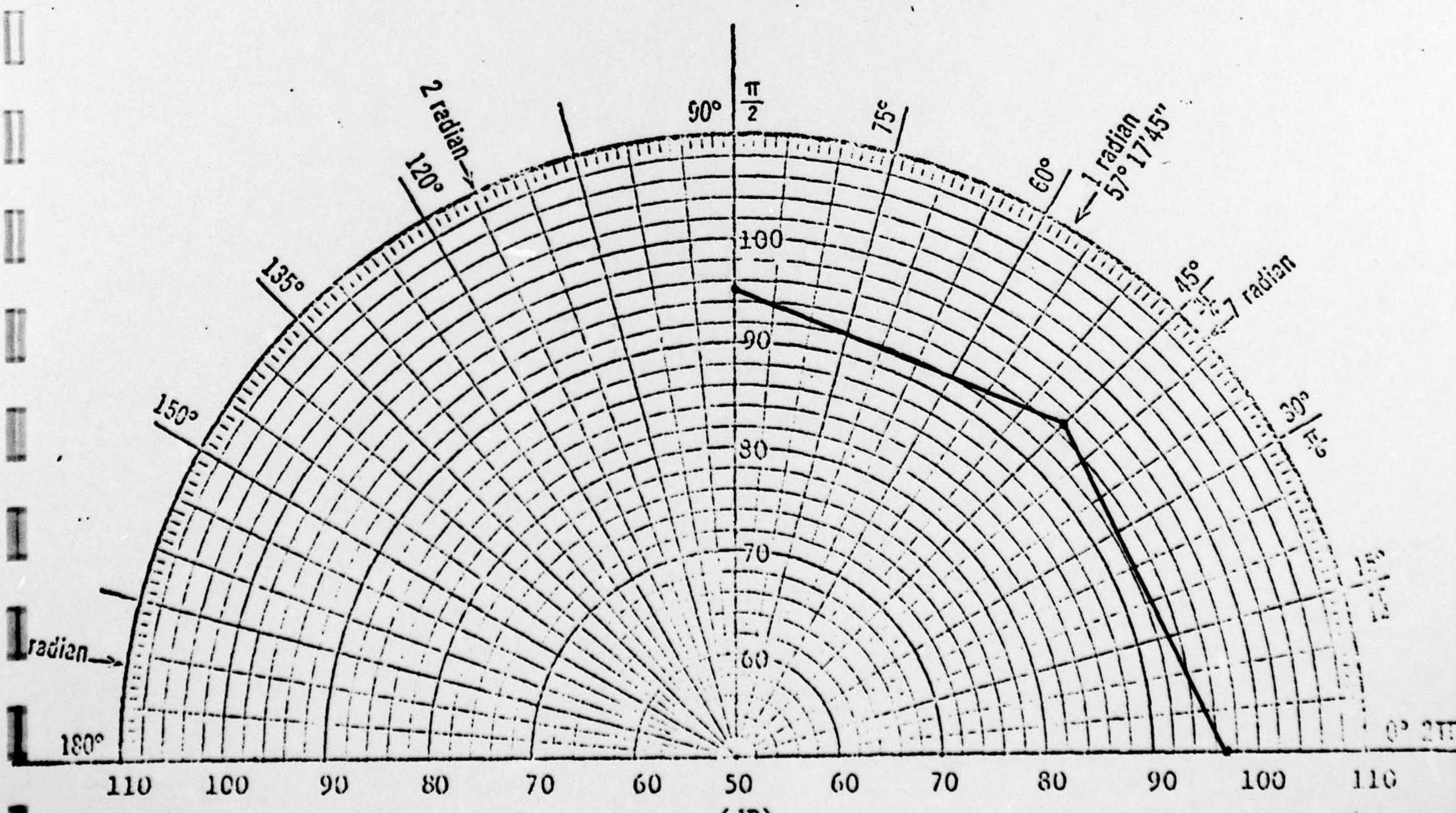


FIGURE 37. Directivity Measurement Scheme for Vibrating Electric Horn #2 Grill Alarm with Double Projector.

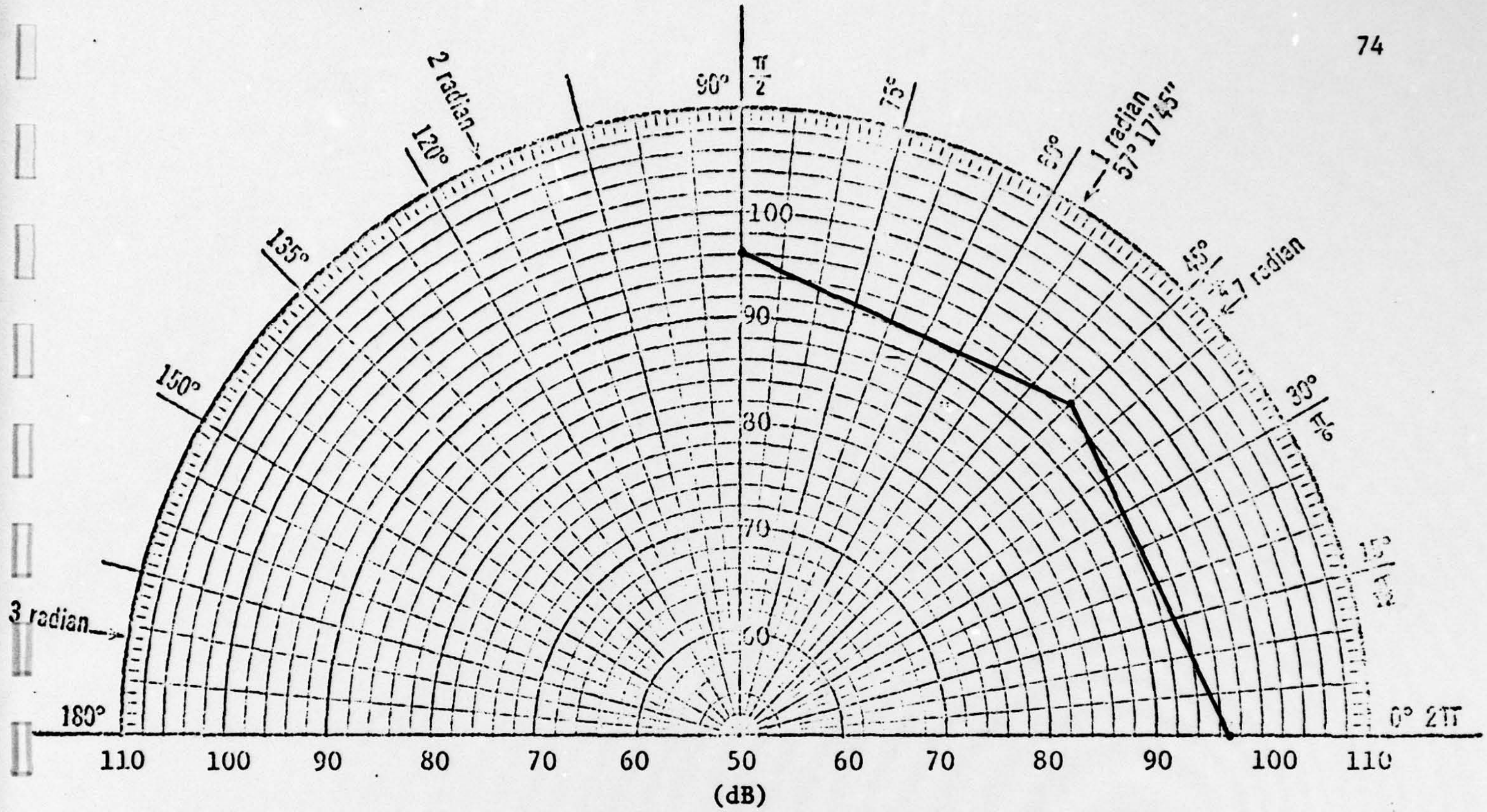


Microphone Height = 9.6"

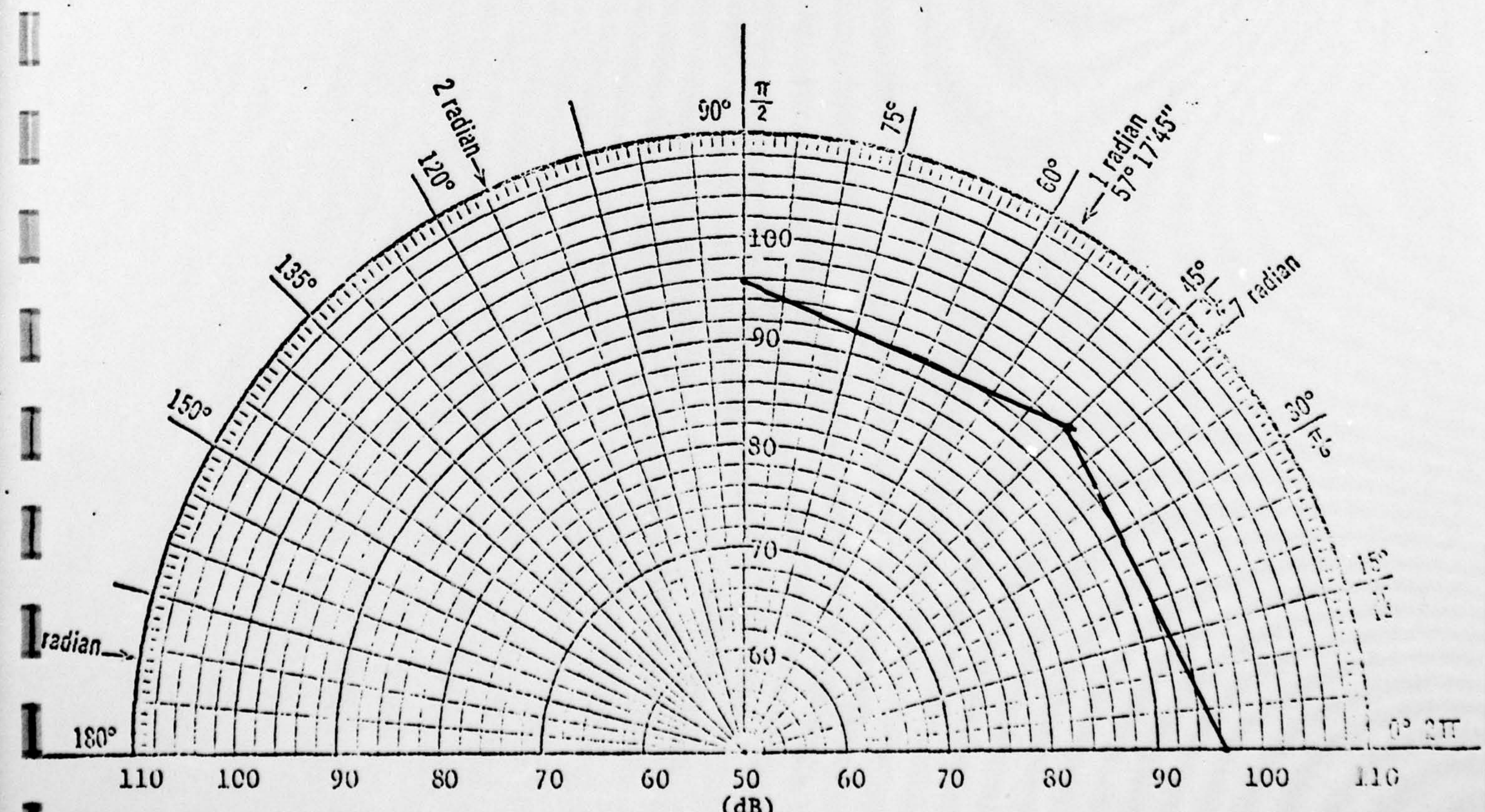


Microphone Height = 19.0"

FIGURE 38. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm with Double Projector.



Microphone Height = 28.7"



Microphone Height = 38.4

FIGURE 39. Directivity Measurements for Vibrating Electric Horn #2 Grill Alarm with Double Projector.

APPENDIX A

AIR ABSORPTION

As sound passes through the atmosphere, it is gradually transformed into heat or absorbed. This absorption is not a factor in small rooms where the number of reflections from the room boundaries is large and the distance the waves must travel between reflections is small. In large rooms, however, the distance travelled for the same number of reflections is much larger and the energy loss due to this distance cannot be neglected. For a wave propagating through air a distance X, the energy density decreases exponentially due to air absorption according to the following formula [19]:

$$D(x) = D_o e^{-mx} \qquad \text{watt-sec/m}^3 \qquad \text{(A-1)}$$

where

m = energy attenuation constant in units of reciprocal length

x = distance travelled in same units as m

Research [9] has shown air absorption can be neglected below 1000 Hz and if the room is sufficiently small (below 283 m^3), it can be ignored entirely. Where it is a factor, however, the constant 4 m has been tabulated for various atmospheric conditions. The value 4 m depends strongly upon frequency and relative humidity and less strongly on temperature. Table A-1 shows how the constant 4 m varies with the atmospheric conditions with frequency as a parameter [19].

TABLE A-1

VALUES OF ENERGY ATTENUATION CONSTANT 4m FOR AIR

Relative Humidity	Temperature °C (°F)	2,000 Hz	4,000 Hz	6,300 Hz	8,000 Hz
30%	15° (59°)	0.0044	0.0148	0.0322	
	20° (68°)	0.0036	0.0116	0.0256	0.041
	25° (77°)	0.0035	0.0095	0.0209	
	30° (86°)	0.0034	0.0086	0.0172	
50%	15° (59°)	0.0030	0.0087	0.0191	
	20° (68°)	0.0029	0.0074	0.0153	0.026
	25° (77°)	0.0029	0.0072	0.0135	
	30° (86°)	0.0028	0.0071	0.0130	
70%	15° (59°)	0.0027	0.0068	0.0138	
	20° (68°)	0.0026	0.0065	0.0122	0.0184
	25° (77°)	0.0026	0.0064	0.0118	
	30° (86°)	0.0025	0.0063	0.0117	

Table A-2 shows the effect of air absorption on the value of the room constant, R:

TABLE A-2

	Octave Band Center Frequency		
	2000	4000	8000
Room Constant w/o Air Absorption (ft^2)	176	216	240
Room Constant w/ Air Absorption (ft^2)	218	320	534

The difference in Room Constant translates to a 3.4 dB difference in sound pressure level output from the ILG reference sound source when the measuring distance is 21 feet. So if calculation procedures were used to estimate the sound power of an unknown source by comparing it with a source of known power, that estimate would be in error by over 3 dB if air absorption was not accounted for.

APPENDIX B

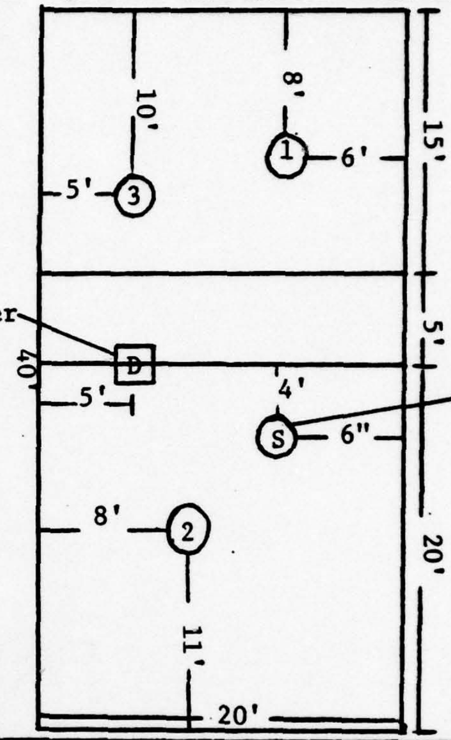
MEASUREMENT DATA SHEETS

All measurements made in the reverberant room occurred on two separate days. On March 20, 1979, the source consisted of the ILG reference sound source. These measurements were taken to evaluate the handball court as a reverberation room. On July 11, 1979, the sound sources were the fire alarms themselves and the diffuser. Figure B-1 and Fig. B-2 show the layout of the handball court for each case.

SOUND LEVEL MEASUREMENT DATA SHEET

1. Date: 11 July 1979
2. Time: 6:30 PM
3. Location: Handball Court 4A
   University of Notre Dame ACC
4. Personnel: Ray Brach, Jim Ernzen and
   Bob Cedoze
5. Source of Sound: Rotating Diffuser and
   Fire Alarms
6. Type of Sound: Impulse ____
   Intermittent ____ Continuous ____
7. Meter B&K 4204 Microphone 1/2" dia.
8. Response: Fast ___ Slow x Weighting ___
9. Tape Calibration Level 124 dB
10. Tape Counter: Calib 5 Record 30
11. Ambient Sound Level 41 dB Loc. ____

Diagram - Source and Instrument Location



		31.25	62.5	125	250	500	1k	2k	4k	8k	16k	Overall
Ambient Sound Level w/o Diffuser			27.0	36.0	33.0	33.0	22.0	22.0	21.0	27	-	41.0 dB
Diffuser Level		65.0	87.0	72.0	63.0	39.0	59.0	51.5	47.0	30.0		87.5

Notes: Diffuser Level measured from microphone Position 2. Ambient A-Weighted Sound Level = 32.0 dBA. Tape Name = Kellie Diffuser A-Weighted Sound Level = 71.0 dBA. "Microphone Height = 4 ft."

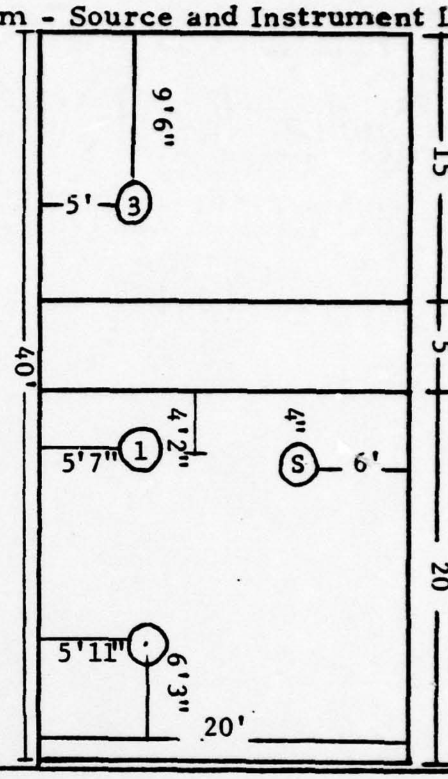
Submitted by: James J. Ernzen Date: 12 July 1979

FIGURE B-2

SOUND LEVEL MEASUREMENT DATA SHEET

1. Date: 20 March 1979
2. Time: 9 AM
3. Location: Handball Court 4A
   Univ. of Notre Dame Athletic Center
4. Personnel: Dr. Brach Jim Ernzen
5. Source of Sound: ILG Reference Sound Source
6. Type of Sound: Impulse ___ Intermittent ___ Continuous X
7. Meter B&K 4304, Microphone 1/2" diameter
8. Response: Fast ___ Slow X Weighting ___
9. Tape Calibration Level 124 dB
10. Tape Counter: Calib 5 Record 30
11. Ambient Sound Level 45 dB Loc. 2

Diagram - Source and Instrument Location



S=Source Location

		31.25	62.5	125	250	500	1k	2k	4k	8k	16k
		Microphone Positions									
		Pos.1		Pos.2		Pos.3					
Standard Source		30-60		65-95		100-130					

Notes: Tape Name = Carborundum "Microphone Height = 4 ft."

Submitted by: James J. Ernzen Date: 22 March 1979

FIGURE B-1

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		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 1LT James J. Ernzen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Student, HQDA, MILPERCEN (DAPC-OPP-E) 200 Stovall Street Alexandria, Va. 22332		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
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Acoustic Response of Fire Alarms
Sound Power level " " "
Fire Alarm Effectiveness (Acoustic)
Emergency Alarm Acoustic Effectiveness

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This thesis deals with the acoustical effectiveness of fire alarm systems. Several single unit commercial and residential fire alarms currently on the market were tested to determine their sound power levels, directivity, and frequency spectra. Facilities used to determine these characteristics included both an anechoic chamber and a reverberation room. The thesis also

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